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A COMPARISON BETWEEN LINEAR PROGRAMMING AND SIMULATION MODELS FOR A DISPACTHING SYSTEM IN OPEN PIT MINES

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A COMPARISON BETWEEN LINEAR PROGRAMMING AND SIMULATION MODELS FOR A DISPACTHING SYSTEM IN OPEN PIT MINES

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DEDICATION

To my best friend,
and my eternal love, my fiancé Mohammad

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RÉSUMÉ

Cette recherche est principalement axée sur la planification de la production à très court terme et de l'affectation des camions aux pelles dans une mine à ciel ouvert. Les principales lacunes des modèles existants dans la littérature sont: a) la non considération du temps d'attente et de la file d'attente aux serveurs (pelles et concasseurs), b) la simplification des modèles et la considération d'une quantité limitée de détails dans les modèles, c) la négligence de la nature stochastique du système d'affectation des camions aux pelles, d) le développement des modèles est basé sur l'hypothèse d'une flotte identique (camions et pelles).

Les objectifs de cette recherche sont le développement et l'utilisation d'un modèle de simulation de base pour valider la solution du modèle de programmation linéaire (PL) et le développement d'un second modèle de simulation qui représente le système de contrôle en temps réel. L'objectif du second modèle de simulation est la maximisation de la production de minerai tout en prenant en compte les contraintes du modèle de PL. Les deux modèles de simulation sont considérés dans les situations déterministes et stochastiques.

Les modèles proposés sont appliqués dans une mine de charbon. Les résultats obtenus à partir de l'exemplaire de base démontrent que le concasseur est le goulot d'étranglement de l'installation. Afin de valider et vérifier les modèles proposés, l'exemplaire de base est modifié pour que les camions et les pelles deviennent à tour de rôle les goulots d'étranglement du système d'exploitation.

Lorsqu'on diminue le nombre de camions pour que ceux-ci deviennent le goulot d'étranglement, le résultat du modèle PL est très optimiste et diffère de la réalité. Le modèle de PL ne considère pas le temps d'attente aux serveurs, mais le modèle de simulation de base tient compte de la file d'attente aux concasseurs et aux pelles. En conséquence, dès qu'on a un temps d'attente dans le modèle de simulation, il y a perte de temps ce qui réduit la production de minerai. Le modèle de simulation en temps réel obtient un meilleur résultat que le modèle de simulation de base. La raison de cette différence est due au fait que dans le deuxième modèle de simulation, la destination pour laquelle on estime qu'il y aura un temps d'attente aux pelles sera pénalisée. La quantité de minerai produite est donc plus grande que dans le modèle de simulation de base.

Quand le temps de chargement de la pelle est considéré comme un goulot d'étranglement, le résultat du second modèle de simulation produit plus de stérile que la solution du modèle de PL.

Étant donné que dans le modèle de PL, l'objectif est de maximiser la production de minerai, il existe plusieurs solutions de même valeur (i.e. même quantité de minerai) mais dont la production de stérile peut fortement varier.

ABSTRACT

This research deals with very short term production plan and truck-shovel hauling system in open pit mines. The main shortcomings of the existing models reviewed in the literature are: a) not considering the waiting time and queue at servers (shovels and crushers), b) simplifying the models and considering a limited amount of details in the models, c) ignoring the stochastic nature of the truck and shovel hauling system, d) developing model based on an homogeneous fleet (trucks and shovels).

The objectives of this research are: 1- to develop and apply a basic simulation model considering the queue and waiting time of trucks at shovels and crushers in both deterministic and stochastic situations based on the linear programming (LP) model result. This model validates the result of the LP model and provides the detailed and applicable dispatching plan for an open pit mine, 2- To develop, apply and verify the second simulation model which is the real time control system. This simulation model maximizes the ore production while taking into account the LP constraints. This model imitates the truck shovel haulage system in both deterministic and stochastic situations.

The proposed models are applied in a coal open pit mine. The obtained results from the LP and simulation models in our case study demonstrate the fact that the crusher is the bottleneck of the system. Then, in order to validate and verify the proposed models, we created two other scenarios where the fleet of trucks and the shovel's service time are considered respectively as bottleneck of the operational system.

When the fleet of trucks is the bottleneck, the result of the LP model is too optimistic and differs from the reality. The LP model does not consider the waiting time at servers while the basic simulation model takes into account the queue at crushers and shovels. As a result, as soon as the waiting time occurs in the simulation model, system is losing time thus the production of ore is lower than the expected. The real time simulation model has better results than the basic simulation model. The reason is that in the second simulation model, the waiting time at shovels will be penalized therefore; this model has a better production level than the basic simulation model.

When the shovel loading time is considered as the bottleneck of the system, the result of the second simulation model produces more waste in comparison with LP model solution. Since in

the LP model, the objective is to maximize the ore production only, there are an infinite number of solutions which have the same level of ore production but different amounts of extracted waste.

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LIST OF ABBREVIATIONS

LP	Linear Programing
MIP	Mixed Integer Programing
NPV	Net Present Value
LOM	Life Of Mine
NN	Neural Network
MR	Multiple Regression
VSTPP	Very Short Term Production Planning
DBS	Deterministic Basic Simulation
SBS	Stochastic Basic Simulation
DRTS	Deterministic Real Time Simulation
SRTS	Stochastic Real Time Simulation

CHAPTER 1: INTRODUCTION

1.1 Problem definition

Open pit mining is a surface mining method of excavating rock or minerals from the ground by removing them from an open pit. This method is used when deposits of valuable minerals or rock are found near the surface. This valuable mineral is called ore which is a natural combination of one or more solid minerals that can be mined, processed and sold at a profit. Also, the non-valuable material is called waste which removing of them in order to reach the ore in an open pit mine is inevitable.

The ore body is excavated from the upper down in sequences of horizontal layers of identical thickness called benches. Mining starts with the highest bench and after an appropriate floor area has been exposed; mining of the next layer begins. The process carries on until the bottom bench height is reached and the final pit out line is achieved. In order to access the different benches, a road or ramp must be prepared (Hustrulid and Kuchta, 1995).

There is a set of operations which will repeat for extracting ore and waste during the life of the mine (LOM). These activities include drilling, blasting, loading and hauling the extracted material to the specific destination. The width and steepness of the ramps and benches in the mine depends upon these operations equipment (Hustrulid and Kuchta, 1995).

Most of the recent open pit designs begin through a geologic block model achieved by dividing the deposit into a three dimensional grid of fixed size blocks, as shown in figure 1-1 (Osanloo et al., 2008).

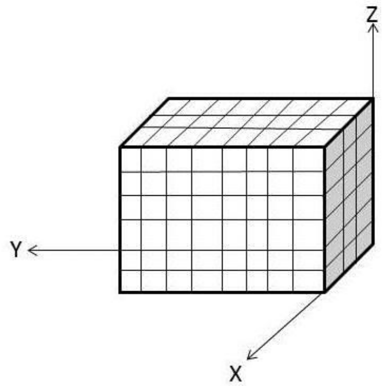

Figure 1- 1: Isometric view of a block model in open pit mine

The grade and various chemical and mechanical properties of the blocks, and also an estimation of their economic value are possible by sampling and the use of geostatistical approaches (Gamache et al., 2009).

The production planning specifies the sequence of mining of these blocks over a definite period of time denoted the scheduling horizon. The production scheduling is usually divided into four levels: long-term, medium-term, short-term and very short-term.

In long-term planning, which is associated with the outlines of the mine that provides the maximum benefit, the goal is to identify which blocks are removed and which one will remain in place. The long-term period is the range of the mine life and depends greatly on the size of the deposit. The medium-term scheduling problem deals with planning horizon between 1 to 5 years. Based on the more detailed information of the medium-term schedules a more precise design of ore extraction from a special area of the mine can be achieved. Also, this information would allow the replacement of necessary equipment or the procurement of required equipment and machinery. The medium-term period also is broken down into 1-6 month periods for even more detailed scheduling.

Furthermore, this period is divided into a shift or one day to a week periods for short term planning. Real time dispatching system is called very short-term planning. The very short-term production planning is a two phases system, that consists in presenting a production plan for a very short-term period that permits better design of the operations and a guide line for dispatching trucks to shovels located in the mining areas.

This thesis will focus on the Very Short-Term Production Planning (VSTPP) in open pit mines. VSTPP determines the number of each type of trucks traveling between each pair of shovel and crusher (or waste dump) for one shift. The model that we will use is the linear programming (LP) model proposed by Gamache et al. (2009). This model provides a production plan for a work shift indicating the number of trucks to be allocated to the different mining areas and the amount of ore and waste extracted by shovels and transported to the crusher or to each waste dump.

The LP model optimizes the ore production considering several constraints. It does not take into account the waiting time and queues at servers such as shovels and crushers. Also, the LP model does not present the operational dispatching plan for trucks in the mine. It only presents the number of truck that has to be sent send to a specific area not the time or their type. Additionally, this is a deterministic model since it considers constant service times at shovels and crushers and constant velocity of the trucks that affect the trucks traveling time.

The first purpose of this research is to apply a discrete event simulation model to open pit mine in order to validate the optimal result of the LP model. In this simulation model, the optimal solution of the LP model is used as a target for the simulator to send the right number of trucks to the mining area whilst providing the operational dispatching plan of trucks in mine. This operational plan presents which truck and when has to be allocated to shovel.

The second purpose of this research is to examine the possibility of developing a simulation model to maximize ore production and determine the number of trips between mining areas and dumping sites that can be used instead of the LP model for a very short-term planning period in an open pit mine.

In the next section the objectives of this research will be presented in more details.

1.2 Research objectives

The performance of the truck and shovel haulage system has been studied in the literature in regard to optimize the objective function through linear programming, simulation models and combination of these methods. In these researches it has been tried to maximize material production or minimize the number of trucks for a specific production plan for a short term.

In this study, a discrete event simulation model is developed to validate the LP model by considering the queue and the waiting time at servers which are ignored by the LP model. The basic simulation model deals with the result of the LP model as a predefined target for dispatching the number of trucks to the shovels and dumping sites. Moreover, another simulation model, that we call a real time simulation model, is developed in order to find a production plan for an open pit mine by considering the LP model constraints through simulation software. So, the general objectives of this research are, to validate the result of the LP model by developing the simulation model, to provide an operational dispatching plan, and to find another way to do the very short-term production planning in open pit mines.

Since the main problem of VSTPP is the uncertainty related to the operations of trucks and shovels in open pit mines, the suggested simulation models deal with the uncertainties consisting of truck velocity, loading time at shovels, unloading time in either crushers or waste dumps.

We can summarize the objectives of this work as:

- To develop and apply a basic simulation model considering the queue and waiting time of trucks at shovels and crushers in both deterministic and stochastic situations based on the LP model result. This model validates the result of the LP model and provides the detailed and applicable dispatching plan for an open pit mine.
- To develop, apply and verify the second simulation model which is the real time control system. This simulation model maximizes the ore production while taking into account the LP constraints. This model imitates the truck shovel haulage system in both deterministic and stochastic situations.
- To compare the result of the LP model and simulation models by considering different scenarios where the main operational components will be in turn the bottleneck of the system.

The next section presents the overall view of this thesis based.

1.3 Thesis structure

In this chapter, an overview of the problem in hand and the research objectives are presented. In chapter 2, the literature review provides an overview of common methodologies and approaches used in studying truck and shovel systems including linear programming, simulation, and combination of these methods. Chapter 3 includes the theoretical framework for the linear programming formulation to optimize the allocation of trucks and shovels as well as describing the simulation models. Chapter 4 is dedicated to the presentation and a discussion of computational results achieved. In chapter 5, some conclusions are drawn and directions for future work are proposed.

CHAPTER 2: LITERATURE REVIEW

This chapter presents the review of studies about the production planning and truck and shovel hauling system. Different approaches have studied this kind of problems in literature. The following classifications are discussed in this chapter.

1. Linear programming
2. Simulation
3. Combination of linear programming and simulation

The planning issues in mining can be represented by mathematical models for distribution of the flow of material on the mine's transportation network. Mathematics programs can be grouped into two classes: linear and nonlinear programming. Soumis et al. (1986) obtained excellent results using a nonlinear programming. Since this research applies the linear programming so, in this thesis only the literature related to the linear programming is presented.

Also, over the last recent decades, simulation has been one of the most respected operational researches tool. The reason for the popularity of the simulation models can be seen in ability and flexibility of this type of method in handling the complex problems. Moreover, simulation models are powerful and also cost effective (Kelton et al., 2007).

This chapter consists of the following sections. In section 2.1, linear programming models used for optimizing the different objective in haulage system for a short-term and very short-term period in an open pit mine are discussed. Section 2.2 focuses on simulation models. Section 2.3 describes the models that combine linear programming and simulation for short term production scheduling in an open pit mine. Section 2.4 presents the methodology of this research and the final section is allocated to the summary of this chapter.

2.1 Linear programming

The first application of the linear programming in truck- shovel hauling system in an open pit mine returns to 1970s (Torkamani and Askari-Nasab, (2012).

Wilke and Reiner (1977) studied the production planning in an open pit mine. They used a linear program whose objective function was to maximize the productivity of the shovel. For each shovel, the authors added a weight in the objective function describing the priority of the shovel. The set of constraints includes blending constraints, capacity constraints of the sources and sinks. The advantages of using a scheme of arbitrary priorities in the objective function make it possible for the objective function to be divided into different technical goals, and it is possible to stop and take into account the major deviations from the long-term production plan. The main disadvantage of this method lies in the fact that it is essential to adjust the weights in the objective blindly to respect the production plan.

Zhang et al. (1990) discussed the optimal allocation of the flow of trucks in an open pit. To make the distribution of trucks to the shovels, the authors use a linear program. The objective function is to minimize the number of trucks required to meet mine production in a short-term horizon. Although the set of constraints is broad and includes the flow conservation, shovels capacity, a minimum level of production, blending constraints, ore and waste ratio, minimum and maximum capacity of the dumping sites, the model ignores other constraints such as those on the capacity of the fleet of trucks.

Gershon et al. (1993) were interested particularly in the problem of finding the appropriate blending of ore in a coal mine. To solve this problem, the authors used a linear program. The objective function of the problem is to minimize the operation costs. In addition to blending constraints, the model makes sure that a minimum level of ore production is achieved. The final mixture of ore must not contain more than a certain maximum amount of sulfur and impurities, and a minimum level of BTU. This kind of problems is easily solvable with the simplex method. The proposed formulation provides an optimal solution to the established scheduling of small and medium complexity problem.

Temeng (1997) proposed to make the production planning using a linear program in an open pit mine by the optimal allocation of the trucks to the shovels. The author used an objective function that has two levels which simultaneously maximize ore production of the shovels and maintain the quality of the ore mixture within acceptable limits defined by the mine. In addition, the author considered several groups of constraints to arrive at a more realistic level of production such as capacity of the shovels, crushers and waste dumps, flow conservation constraint, blending constraint, stripping ratio, and the number of trucks. However, this model does not consider the truck cycle time in the mine.

Temeng et al. (1997) combined goal programming model with the transportation algorithm as a real time dispatcher in order to maximize production and minimize the total waiting time of shovels and trucks. The objective function of the goal programming model includes production rate and ore grade, to present the importance of both production and ore quality in company's goals. This model optimizes the total production by considering routes between mining areas and their destinations. In order to optimize the production, routes having the shortest cycle time are selected. Then, according to the transportation models the trucks are allocated to the shovels which minimize the cumulative deviations of the optimal production target. The transportation model attempts to minimize total waiting time of shovels and trucks. Moreover, the effect of the shovels and trucks breakdowns on quality of dispatching model is tested in this paper.

The work of Burt et al. (2005) focused on the optimal allocation of trucks to the shovels. To do this allocation, they use a linear programming model where the objective function is to minimize the cost of operation of the trucks and shovels fleet. The set of constraints of the model includes the productivity of trucks and shovels and the minimum production. The major difference of this article is the desire of the authors to obtain a production plan reflecting high productivity of the equipment. In this regard, they use a match factor that is a measure of the productivity of the fleet. The match factor is the ratio of the productivity of the trucks and shovels for a homogeneous fleet of trucks. The article does not consider the waiting time at shovels, but they propose a method for modeling the waiting time which would depend on the inter arrival time of the trucks at shovels. Unfortunately, this model uses average cost of equipment that is not realistic and does not consider the global optimization for mine.

The paper by Rubito (2007) concentrated on the optimal allocation of trucks to the crushers in the mine. The author uses a linear program where the objective function is to maximize profits of sending the trucks to the various crushers. The only constraints of this model include capacity constraints of shovels which make the proposed model as a simple model that cannot be useful for the more complex problems.

Ercelebi and Bascetin (2009) studied a truck and shovel system of a coal mine in Turkey. This work has two stages. In the first stage: the optimal numbers of trucks are determined by the closed queuing network model. In the second stage, LP model aids how to dispatch the trucks to shovels. The LP model minimizes the number of trucks on the road, number of trucks at shovels and number of trucks at dump site which assumes no truck queuing under ideal conditions. Although this model guarantees maximum shovel utilization, it cannot be functional in the complex models with other desirable constraints.

Gamache et al. (2009) developed a generic linear programming model to optimize an open pit mine production plan. The proposed model presents a production plan for a work shift considering several constraints such as blending constraint, capacity of equipment, stripping ratio, the amount of available material infront of each shovel, etc. After developing the basic model, authors tried to lineraize a set of constraints that calculates the waiting time of trucks at shovels and crushers. For this thesis the basic model does not consider the waiting time at sevice points. The experiments and the results of this paper present a more realistic production plan for a working shift. It is worth mentioning that the basic model of the above paper will be used in order to accomplish the reaserch.

Topal and Ramazan (2010) minimized the truck maintenance costs developing a Mixed Integer Programming (MIP) model for a large scale gold mine in Western Australia. The MIP model in order to create an optimal truck schedule uses the total hours of truck usage (truck age), maintenance cost and essential operational hours. Although the presented MIP model optimizes the utilization of truck over the life of mine, this model is developed for a long time period and has to be simplified to be applicable for a short-term and very short-term period.

Another multi stage approaches for hauling system in mine was made by Gurgur et al. (2011). They used LP model to optimize allocation of trucks using interactively and simultaneously of MIP model for short-term and long-term mine production planning. The MIP model maximizes the NPV by optimizing the material movement with respect to the ore quality and also precedence constraints. LP model minimizes the deviation of actual movement of material from the predefined target. Availability of fleet including the number and size of the trucks and road profile are the LP model constraints. The proposed LP model can be efficient only using the developed MIP model.

Considering the reviewed literature, there are several ways to model a production plan in a mine by a linear program. The choice of objective function is extensive and can greatly influence the behavior of the model. Several techniques exist to incorporate groups of constraints in the mathematical program, which depend on the problem. Although linear programming methods have applied in the literature since 1970s for truck shovel dispatching, they have some limitations. The most significant shortcomings of these models are:

1- Simplifying the models and considering a limited amount of details in the model. For example, considering the limited constraints and providing the simple model which does not include the whole aspects of the haulage system. Also, using the identical equipment in terms of the capacity and speed of trucks and shovels.
2- Not considering the waiting time at servers (shovels and crushers)
3- Not taking into account the stochastic nature of the hauling systems (truck and shovel transporting system) which are the uncertainties of the loading, unloading, traveling times and ore grades (Gurgur, Dagdelen, & Artittong, 2011).

Also, most of the researches have been studied the long-term period which emphasizes the necessity of more studies for the short-term and very short-term period.

2.2 Simulation

Simulation has been used in both open pit and underground mines in material handling and truck and shovel hauling systems, mining operations, production scheduling and mine planning (Yuriy & Vayenas, 2008).

Castillo and Cochran (1987) studied a truck dispatching system in a copper mine. In their study, the fleet size is known and the fixed dispatch strategy is used to allocate trucks to shovels. This means that trucks must travel between the same destinations during the shift. A microcomputer simulation model is developed using SLAM II, to compare the suggested dispatching procedure to the current one. This algorithm gives the priority to the shovels in ore areas to maximize ore production and maximizes utilization of the truck. The presented simulation model follows the fixed assignment strategy which is the main disadvantage of the system because, this strategy reduces the efficiency of the truck and shovel capacity in the mine.

Sturgul and Eharrison (1987) simulated three different dispatching systems of three open pit mines in Australia. The first dispatching system is applied in a coal mine. This system increases the production; however it causes an extra cost. In the second example, the accurate number of trucks is estimated to optimize the production of uranium mine. In this case study, each truck is allocated to a specific shovel for the shift. The third case study is again in a coal mine using a truck and shovel hauling system. Simulation model tries to estimate the correct number of trucks. A hauling system using conveyor belt is also considered as an alternative. This work also follows the fixed dispatch and assignment strategy.

Bonates and Lizotte (1988) developed a computer simulation model for an open pit mine based on FORTRAN programming language. They propose different dispatching strategies such as maximizing trucks and shovels utilization and fixed dispatch. This simulation model attempts to respect the long term production objectives. Each of these policies has its own advantages and disadvantages. Maximizing truck utilization causes higher production but it is not always the best policy all the time. For example, when the difference between traveling time of truck among shovels is significant or system has to also consider the grade quality of ore. Since, the objective is to maximize truck utilization so trucks will be allocated to the nearest shovels and then the further shovel will be idle for longer time that causes the unbalances in the system. On the other hand maximizing shovel utilization results on the same operating rate for all of the shovels that is more desirable. The efficiency of these policies depends on the available number of trucks. Moreover, the developed simulation model follows the fixed dispatch strategy.

Peng et al. (1988) proposed a simulation model for an iron mine in northeast China. This semi continuous open pit mine has a discontinuous truck and shovel hauling system and a continuous belt elevator system. The proposed simulation model used to define the optimal number and the size of the shovels to work with crushers, the number of trucks, the size of the crusher and the size of the storage for a specific crusher and conveyor system. In summary they try to study the effect of the various type of the equipment on the production rate. This model does not consider the uncertainties of the operational system in the proposed simulation model.

Forsman et al. (1993) applied a simulation model into an open pit copper mine in northern Sweden. This model is similar to one proposed in Bonates and Lizotte (1988) work, but in this model a graphical animation is also presented. By maximizing the shovel utilization, the total tonnage of production will decrease. Maximizing the truck utilization results in the same total tonnages as fixed dispatching model, but the tonnage of ore is lower. The developed model also makes decisions about setting up a crusher in the pit, purchasing new trucks, and planning a route for effective material carrying.

Karami et al. (1996) developed a simulation model to study truck and shovel hauling systems in an open pit mine using SLAM II. They consider the fix assignment of trucks to the shovels in the transportation system. The model is applied to understand the behavior of the hauling system under different configurations and to evaluate the operating performance.

Ataeepour and Baafi (1999) studied the impact of dispatching rule on system productivity using the simulation model. They considered the dispatching and non-dispatching mode in the research. In a non-dispatching mode, each truck keeps its shovel allocation, for example a mine with five shovels is similar to five mines with one shovel each except that there is a shared dumpsite. These procedures attempts to maximize using of shovels or trucks in the system that actually minimize the waiting time of trucks at shovels. In this regard, the arrival time of a truck at each shovel and the time the shovel starts loading the truck have been calculated. Therefore, the dispatcher sends a truck to a shovel, which results in the least delay time for the truck. Their model assumes that all trucks in the mine are the same in terms of capacity; engine power, speed, etc.

Awuah-Offei et al. (2003) used simulation to predict the truck and shovel requirements of a gold mine for a four years period which was important for the mining contractor to know the equipment needs in advance. Trucks are considered as entities and processes include the arrival of entities, loading, and movement of entities, unloading and queuing. The historical data for loading and unloading time, traveling time and failure of the shovels are collected and the appropriate functions are fitted. Average queue length of trucks at the shovel, average shovel utilization per shift and number of trucks loaded per shift is the specific results of this program but, this model was developed for a long term period.

Yuriy and Vayenas (2008), are an instance of the researchers who combine the mathematical programming model with a simulation model. They use a genetic algorithm to develop a reliable model for providing the times between failures in order to combine it by arena simulation model for maintenance analysis of mining equipment. They estimate the time between failures for each fleet as input for the arena simulation model. The simulation model imitates the operations in the mine to evaluate the effect of failures on production rate, and to estimate fleet availability and utilization. This simulation models does not take into account the failure of the equipment. They also do not consider which equipment has the critical role on production quantity.

Comparisons between the application of simulation models and other operation research methods are also stated in the literature. For example, Chanda and Gardiner (2010) use computer simulation, neural networks (NNs) and multiple regressions (MRs) to estimate the truck cycle time in a large gold mine in Western Australia. They only study the travel time of empty and loaded truck as a cycle time. The deviations from the actual cycle time of trucks used to compare the above methods. Authors show that although the simulation is the most common method in this field but it usually overrates or miscalculates the cycle time. Also, the developed model for forecasting the cycle time applies to a specific mine site and it cannot be directly apply to other operations.

2.3 Combination of linear programming and simulation models

Combination of the linear programming model and a simulation model also exist in the literature. In these problems, mathematical models are used for solving the allocation problem and simulation for the real time dispatching problem.

Fioroni et al. (2008) used an optimization model and a simulation model to generate short-term planning plans. They create monthly schedule of an open pit mine using Arena simulation software and Lingo optimization software. The objective of the LP model using Lingo software is to find the initial allocation of the loader and transportation equipment. The objective of the simulation model using Arena is to identify the number of trips of trucks in each area respecting the grade of ore during the simulation period. At first, the initial number of trucks and shovels are calculated using the optimization model. Then, using the result of the optimizer, simulation model will run until a failure occurs in the system therefore, the optimizer will calculate the new plan and this procedure will continue for the period of one month. They use simulation model to allow the feasibility of the mining plan proposed by optimizer, giving utilization and production. This work is based on the optimizer model and relies on the result of that.

Torkamani and Askari-Nasab (2012) developed and implemented a simulation model to analyze the truck and shovel haulage system in a copper mine. The developed approach assures the optimum Net Present Value (NPV) in long-term scheduling and short-term scheduling periods objectives. The developed model considers the optimal short-term schedule in simulation model while considering the uncertainties related with the manoeuvre of trucks and shovels, loading and dumping time. In the proposed model an entity is a mining-cut portion removed at each period and sent to a certain destination. Trucks, shovels, and loaders are resources in the simulation model. This approach has two stages which short-term scheduling plans are the basis for building the model. These two stages are as follows.

In the first stage using the MIP model, several scenarios are created with a different number of trucks and shovels and they are examined to define the essential number of each resource. In the second stage, using the result of the first stage, the system is simulated in Arena and the developed model is evaluated. One of the main advantages of this model is in founding the required number of trucks and shovels based on the short-term mine plan not only based on the shovel’s requirements. But, the proposed simulation model assumes that all trucks and all shovels are identical.

2.4 Methodology

As it can be seen form the literature, the proposed models in the literature have limitations and shortcomings to solve the production planning in an open pit mine which are:

1- Ignoring the waiting time at servers (shovels and crushers)
2- Simplifying the models and considering a limited amount of details in the models
3- Ignoring the stochastic nature of the truck and shovel hauling system
4- Developing model based on the identical fleet (trucks and shovels)

Discrete event simulation model will be applied in this thesis to overcome the presented limitations and shortcomings. The current research will overcome these limitations by considering the LP model proposed by Gamache et al. (2009) for a very short-term production plan. Their model is a complete linear programming that is used to maximize the ore production respecting several constraints. This model approximate waiting time at service points in an open pit mine but, we use the basic linear model of their model which does not consider the waiting time at servers. The basic simulation model will apply to validate the result of the LP model considering the waiting time and queue of trucks at servers during the time period. Besides, in order to find a new way of very short-term production planning the second simulation model which is the real time control system developed. The real time simulation model presents the truck and shovel hauling system with more details in order to provide a new model with enough details to overcome the shortcomings of the literature.

In order to consider the uncertainties of the hauling systems, randomness variables are added to the deterministic simulation models. These models take into account the uncertainties of loading time, unloading time and traveling times. One of the main contributions of this work is that the proposed simulation model can work when a heterogeneous fleet of trucks and shovels is used, which is something that we haven’t seen in the literature.

Based on these observations, we propose the following procedure for the development of a new dispatching system in an open pit mine:

- Develop and solve a linear programming model to allocate trucks to the shovels. The optimal solution of this model will indicate the amount of ore and waste to be transported during the shift between shovels and crushers or waste dumps. The objective of LP model is to maximize the ore production with respect to the blending constraints, strip ratio, flow conservations constraints, mining capacity, cycle time constraints, etc.
- Implement two different simulation models (a basic simulation model and a real time simulation model) that will use different types of trucks as entities and the shovels as resource of the simulation.
- Use the basic simulation model to test the accuracy of the LP model. To achieve that the simulation model will use the optimal solution of the LP model (more precisely the number of trips of the different type of trucks at each shovel) as input.
- Use the real time simulation model to imitate the real system considering the LP constraints. This model is developed in order to find the new way of very short-term production planning.
- Create different bottleneck situations of the shovel truck haulage system in order to evaluate different configurations to better evaluate the new dispatching system.

2.5 Summary and Remarks

In this chapter the related literature of two different approaches in regard to evaluating the truck and shovel systems were presented. Obviously, the ability of accurately assessing a transporting performance of system is vital for mining companies. Any improvement in the performance of system would save a considerable quantity of money. Because of the complexity of the hauling system in mine, this assessment is not an easy task. This complexity is coming from stochastic features of the system. In the next chapter the theoretical models which are developed in this thesis will be presented.

CHAPTER 3: THEORITICAL MODELS

The objective of this chapter is to present the theoretical models which are developed in order to reach the objective of this thesis. First in this chapter the LP model that maximizes the total ore production during the shift will be presented. The result of the LP model is a very short-term production plan which is used as a guide line for the dispatching system. The LP model does not take into account the waiting time at servers and does not present the operational dispatching plan. To validate the result of the LP model we will develop a simulation model named the basic simulation model. The basic simulation model takes into account the waiting time at servers and provides the operational dispatching plan for an open pit mine considering the optimal solution of LP model as target for allocating the trucks to the shovels in mining areas.

The second simulation model is a real time simulation model, which imitates the real problem to determine the required number of trucks to allocate to shovels. This model takes into account the characteristics of the mine’s material content in mining areas and considers the ratio between sterile material and the production of total material. With this model, the possibility of presenting a new way of VSTPP will be tested.

Furthermore, since LP model and also simulation models are based on the deterministic input data, so; at the end of this chapter, both simulation models are considered in the stochastic situations. The stochastic simulation models involve uncertainties associated with the trucks, shovels and crusher operations into the model.

Details of each proposed model are explained in the following sections. Section 3.1 introduces the LP model formulation for VSTPP generated by Gamache et al. (2009). Section 3.2 describes the simulation models (the basic and real time simulation models) as deterministic models and stochastic models. Finally Section 3.3 presents the summary and remarks. The next section introduces the linear programming model for very short-term production planning (VSTPP) in an open pit mine.

3.1 Linear Programing (LP) model

We first present a linear programming (LP) model which creates an open pit mine's production plan for a shift. This model, based on Gamache et al. (2009), maximizes ore production during the shift by considering the blending constraints, stripping ratio, flow conservation constraints, mining capacity constraints, etc.

3.1.1 Notations

The following notations are used in the proposed model.

I	Mining areas (ore and waste)
$J = J_c \cup J_w$	Sets of crusher (subscripts c) and waste (subscripts w)
K	Set of trucks

Indices

$i \in I$	Index for mining areas
$j \in J$	Index for crushers and waste dumps
$k \in K$	Index for types of trucks

Parameter

CA_k	Capacity of a truck of type k (in tons)

The main variables of the LP model are:

X_{ijk}	Number of type k trucks carrying material from shovel i to destination j (crusher or waste dumps) per shift. (Full trucks)
Y_{jik}	Number of trucks of type k traveling empty from destination j to the mining area i per shift. (Empty trucks)

3.1.2 Objective function

The objective is to maximize the total ore production in the mine for a shift. In this regard, it would be sufficient to maximize the number of trips between ore areas and crusher. As the truck fleet is heterogeneous, the total production of ore associated with the number of travels between the mining areas (source) and dumping sites (sink) depends on the type of trucks that has been used. For this reason, we must multiply the capacity of each type of truck (CA_k) by the total number of trips between mining areas and crushers.

The objective function of the LP model is:

$$\text{Maximize } z = \sum_{i \in I} \sum_{j \in J_c} \sum_{k \in K} CA_k \, . X_{ijk} \tag{3.1}$$

3.1.3 Constraints

Flow conservation

These constraints are used to balance the flow for each type of trucks at each service points (shovels, crushers, and waste dumps) in the mine. They are used to ensure that, for each source, the number of incoming empty trucks is equal to the number of outgoing loaded trucks.

In the case of the dumping sites, the number of loaded trucks arriving at each unloading site must be equal to the number of empty trucks leaving that site.

$$\sum_{i \in I} X_{ijk} - \sum_{i \in I} Y_{jik} = 0 \qquad \forall j \in J, \forall k \in K \tag{3.2}$$

$$\sum_{j \in J} X_{ijk} - \sum_{j \in J} Y_{jik} = 0 \qquad \forall i \in I, \forall k \in K \tag{3.3}$$

Capacity constraints at crusher and waste dumps

This set of constraints ensures that the capacity of crusher and waste dumps is respected. Before explaining these constraints, we must define parameters that are used in these constraints. The value of these parameters depends on type of the equipment.

CJ_j^U Maximum capacity of each destination j (crusher or waste dumps) in tons per shift

CJ_j^L Minimum capacity of each destination j (crusher or waste dumps) in tons per shift

Commonly, we can assume that the maximum capacity at waste dumps is very large. In this case, there is no need to consider this constraint. However, for purposes of consistency of notation, we consider it as follows. Moreover, the minimum capacity should be seen as a minimum requirement of material at these destinations.

$$\sum_{i\in I}\sum_{k\in K} \mathrm{CA}_k.\ \mathrm{X}_{ijk} \leq \mathrm{CJ}_j^U \qquad \forall j \in J \tag{3.4}$$

$$\sum_{i\in I}\sum_{k\in K} \mathrm{CA}_k.\ \mathrm{X}_{ijk} \geq \mathrm{CJ}_j^L \qquad \forall j \in J \tag{3.5}$$

Capacity constraints of shovels in mining areas

This set of constraints presents capacity of each shovel in mining areas. To do this, we need to define some parameters first

CI_i^U Maximum tonnage of material in front of each shovel i which could be extracted

CI_i^L Minimum tonnage of material in front of each shovel i which could be extracted

The maximum tonnage of material in front of each shovel i which could be extracted depends on two parameters, ρ (tonnage of material available at shovel i) and δ (capacity of shovel i in tons per shift). In fact CI_i^U is the minimum of ρ and δ .

$$\mathrm{CI_i^U} = \min\{\rho, \delta\} \qquad \forall i \in I \tag{3.6}$$

Thus, the capacity constraints at each shovel in mining areas are:

$$\sum_{j \in J} \sum_{k \in K} \mathrm{CA_k} .\ \mathrm{X_{ijk}} \le \mathrm{CI_j^U} \qquad \forall i \in I \tag{3.7}$$

$$\sum_{j \in J} \sum_{k \in K} \mathrm{CA_k} .\ \mathrm{X_{ijk}} \ge \mathrm{CI_j^L} \qquad \forall i \in I \tag{3.8}$$

Blending constraints

Blending constraints are added into the model to guarantee the acceptable quantity of each characteristic of ore that enters in the crushers. We need lower and upper limits of different characteristics of ore to obtain a mixture in valid intervals. The following parameters are defined according to the desired type of mixture.

B All the characteristics of ore

$\mathrm{A_{ib}}$ The typical characteristic value of b at each shovel i per ton

$\mathrm{A_{jb}^L}$ and $\mathrm{A_{jb}^U}$ The lower and upper values of each characteristic b per ton to obtain the desirable mixture at crusher per shift.

These parameters should be adjusted to reflect the content of the ore characteristics at the beginning of each shift.

For each crusher, there are two sets of blending constraints:

$$\sum_{i \in I} \sum_{k \in K} (A_{ib} - A_{jb}^{L}) . CA_k . X_{ijk} \geq 0 \qquad \forall j \in J_c, \forall b \in B \tag{3.9}$$

$$\sum_{i \in I} \sum_{k \in K} (-A_{ib} + A_{jb}^{U}) . CA_k . X_{ijk} \geq 0 \qquad \forall j \in J_c, \forall b \in B \tag{3.10}$$

These constraints can also be global for all crushers. In this case the constraints can be written as:

$$\sum_{j \in J_c} \sum_{i \in I} \sum_{k \in K} (A_{ib} - A_{jb}^{L}) . CA_k . X_{ijk} \geq 0 \qquad \forall b \in B \tag{3.11}$$

$$\sum_{j \in J_c} \sum_{i \in I} \sum_{k \in K} (-A_{ib} + A_{jb}^{U}) . CA_k . X_{ijk} \geq 0 \qquad \forall b \in B \tag{3.12}$$

Stripping ratio

This constraint must be added to ensure a sufficient production of waste, in order to facilitate access to the mineralized and valuable zones in the future.

R_{min} : is the minimum ratio of the production of sterile in comparison to the total production of material.

$$\sum_{i \in I} \sum_{j \in J_w} \sum_{k \in K} CA_k . X_{ijk} - R_{min} . \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} CA_k . X_{ijk} \geq 0 \tag{3.13}$$

Minimum ore production

This global constraint requires a minimum amount of ore production during the shift.

D Minimum request of ore production for the shift in tons

$$\sum_{i \in I} \sum_{j \in J_c} \sum_{k \in K} CA_k . X_{ijk} \quad \geq D \tag{3.14}$$

Truck capacity (cycle time)

The capacity of the truck is defined as the total available time of all trucks during the duration of the shift. This capacity must not be exceeded by the time of use of trucks which includes travel time and service time (loading or unloading). Although Gamache et al. (2009) approximated the waiting time at shovels and crushers in their paper but, we use the basic model which does not consider the waiting times.

First we need to define new parameters:

T_{ijk}^{F} Travel time of a full truck of type k between the mining area i and crusher or waste dumps j

T_{jk}^{Un} Unloading time of truck type k at crusher or waste dumps j

T_{jik}^{E} Travel time of an empty truck type k between crusher or waste dumps i and the mining area i

T_{ik}^{Lo} Loading time of truck type k at shovel i

For a truck of type k, utilization time from source i to sink j can be written as follows:

$$\mathrm{T}^{\mathrm{k}}_{\mathrm{Utilization},(\mathrm{i}\rightarrow \mathrm{j})} = \mathrm{T}^{\mathrm{F}}_{\mathrm{ijk}} + \mathrm{T}^{\mathrm{Un}}_{\mathrm{jk}} \tag{3.15}$$

And for the return part, utilization time from sink j to source i is as follows:

$$\mathrm{T}^{\mathrm{k}}_{\mathrm{Utilization},(\mathrm{j}\rightarrow \mathrm{i})} = \mathrm{T}^{\mathrm{E}}_{\mathrm{ijk}} + \mathrm{T}^{\mathrm{Lo}}_{\mathrm{ik}} \tag{3.16}$$

$T^{F}_{ijk}, T^{Un}_{jk}, T^{E}_{jik}$ and T^{Lo}_{ik} are the constant numbers which can be properly estimated by the mine planners.

Therefore, truck cycle time capacity is as follows:

$$\sum_{\mathrm{i}\in \mathrm{I}} \sum_{\mathrm{j}\in \mathrm{J}} \left(\mathrm{T}^{\mathrm{F}}_{\mathrm{ijk}} + \mathrm{T}^{\mathrm{Un}}_{\mathrm{jk}}\right).\mathrm{X}_{\mathrm{ijk}} + \left(\mathrm{T}^{\mathrm{E}}_{\mathrm{jik}} + \mathrm{T}^{\mathrm{Lo}}_{\mathrm{ik}}\right).\mathrm{Y}_{\mathrm{jik}} \leq T^{shift} \quad \forall k \in K \tag{3.17}$$

And, T^{shift} is the total available time in the shift

Capacity of service time at shovels, crusher and waste dumps

These constraints present the capacity of shovels at each mining area, crusher and waste dumps in terms of the loading and unloading time which cannot exceed the total available time during the shift.

$$\sum_{k\in K} T^{Lo}_{ik}.\mathrm{Y}_{\mathrm{jik}} \leq T^{shift} \qquad \forall\, i \in I \tag{3.18}$$

$$\sum_{k\in K} T^{Un}_{jk}.\mathrm{X}_{\mathrm{ijk}} \leq T^{shift} \qquad \forall j \in J \tag{3.19}$$

Integer and non-negativity constraints

These constraints guarantee the integrality and non-negativity of variables in the model.

$$X_{ijk} \in \mathbb{N} \text{ and } X_{ijk} \geq 0 \qquad \forall i \in I, \forall j \in J, \forall k \in K \tag{3.20}$$

$$Y_{jik} \in \mathbb{N} \text{ and } Y_{jik} \geq 0 \qquad \forall i \in I, \forall j \in J, \forall k \in K \tag{3.21}$$

Complete model

Now we can write the complete model which includes flow conservation, capacity constraints at crusher and waste dumps, capacity constraints at shovels in mining areas, blending constraints, strip ratio, minimum ore production, truck capacity (cycle time), capacity of service time at shovels, crusher and waste dumps and integer and non-negative variables.

$$\text{Maximize } z = \sum_{i \in I} \sum_{j \in J_c} \sum_{k \in K} CA_k . X_{ijk} \tag{3.22}$$

Subject to:

$$\sum_{i \in I} X_{ijk} - \sum_{i \in I} Y_{jik} = 0 \qquad \forall j \in J, \forall k \in K \tag{3.23}$$

$$\sum_{j \in J} X_{ijk} - \sum_{j \in J} Y_{jik} = 0 \qquad \forall i \in I, \forall k \in K \tag{3.24}$$

$$\sum_{i \in I} \sum_{k \in K} CA_k . X_{ijk} \leq CJ_j^U \qquad \forall j \in J \tag{3.25}$$

$$\sum_{i \in I} \sum_{k \in K} CA_k . X_{ijk} \geq CJ_j^L \qquad \forall j \in J \tag{3.26}$$

$$\sum_{j\in J}\sum_{k\in K} CA_k.\ X_{ijk} \ \leq CI_j^U \qquad \forall \mathrm{i} \in \mathrm{I} \tag{3.27}$$

$$\sum_{j\in J}\sum_{k\in K} CA_k.\ X_{ijk} \ \geq \ CI_j^L \qquad \forall \mathrm{i} \in \mathrm{I} \tag{3.28}$$

$$\sum_{j\in \mathrm{J}_c}\sum_{i\in I}\sum_{k\in K}\left(A_{ib} - \ A_{jb}^L\right).CA_k.X_{ijk} \ \geq 0 \qquad \forall \mathrm{b} \in \mathrm{B} \tag{3.29}$$

$$\sum_{j\in \mathrm{J}_c}\sum_{i\in I}\sum_{k\in K}\left(-A_{ib} + \ A_{jb}^U\right).CA_k.X_{ijk} \ \geq 0 \qquad \forall \mathrm{b} \in \mathrm{B} \tag{3.30}$$

$$\sum_{i\in I}\sum_{j\in J_s}\sum_{k\in K} CA_k.X_{ijk} - R_{min}.\sum_{i\in I}\sum_{j\in \mathrm{J_c}}\sum_{k\in K} CA_k.X_{ijk} \quad \geq 0 \tag{3.31}$$

$$\sum_{i\in I}\sum_{j\in J_c}\sum_{k\in K} CA_k.X_{ijk} \quad \geq D \tag{3.32}$$

$$\sum_{\mathrm{i}\in\mathrm{I}}\sum_{\mathrm{j}\in\mathrm{J}}\left(\mathrm{T_{ijk}^F} + \ \mathrm{T_{jk}^{Un}}\right).\mathrm{X_{ijk}} + \left(\mathrm{T_{jik}^E} + \ \mathrm{T_{ik}^{Lo}}\right).\mathrm{Y_{jik}} \ \leq \ T^{shift} \quad \forall k \in K \tag{3.33}$$

$$\sum_{k\in K} T_{ik}^{Lo}.\mathrm{Y_{jik}} \ \leq T^{shift} \qquad \forall i \in I \tag{3.34}$$

$$\sum_{k\in K} T_{jk}^{Un}.\mathrm{X_{ijk}} \leq T^{shift} \qquad \forall j \in J \tag{3.35}$$

$$X_{ijk} \in \mathbb{N} \text{ and } \quad X_{ijk} \geq 0 \qquad \forall i \in I, \forall j \in J, \forall k \in K \tag{3.36}$$

$$Y_{jik} \in \mathbb{N} \text{ and } Y_{jik} \geq 0 \qquad \forall i \in I, \forall j \in J, \forall k \in K \tag{3.37}$$

This section presented the linear programming model for a VSTPP in an open pit mine, which maximizes ore production during a shift according to the required constraints. The LP model doesn't take into account the waiting time at shovels and crushers. In the following section, the simulation models are presented in order to validate the optimal result of the LP model and to find a new way for VSTPP.

3.2 General concepts and definition of simulation models

In this thesis, we present two simulation models. The first model, called basic simulation model, considers the queue and waiting times at shovels in mining areas and crushers in dumping sites. This simulation model is used to validate the optimal result of the LP model which is related to truck and shovel hauling system. The LP solution indicates the number of trips between sources and sinks in terms of the number of empty and full trucks that should be traveling between dumping sites and mining areas. The basic simulation model uses the optimal result of the LP model as a target for allocating trucks to the mining areas.

To assess the possibility of finding and proposing a new way for production planning for a very short-term period, a second simulation model, called the real time simulation model, is developed. This simulation model imitates the real hauling system of the mine and takes into account all constrains of the VSTPP. Its objective is to maximize ore production.

The suggested simulation models are developed in Arena (Rockwell Automation, 2012) simulation software. Arena is one of the common simulation modeling tools, because it has a powerful and operational user base (Rossetti, 2009).

In the next section the general assumptions of simulation models are presented.

3.2.1 Assumptions

To develop simulation models, some basic assumptions which are considered in this work are as follows:

- All shovels and crushers can serve only one truck at a time and trucks might be in the queue at mining areas or in the crusher to be served
- The crusher is considered as the parking lot at the beginning and at the end of the shift
- During the running of the simulation models, the truck and shovels system are operating without following any schedule.

The necessary definitions applied in simulation models are introduced in the following section.

3.2.2 Definitions

In this thesis, the ***Entities*** of the simulation models are the trucks; for example if we have two types of trucks, we will have two different entities.

In these simulation models, loading and unloading the trucks are considered as ***Process*** and the essential ***Resources*** for these processes are shovels in mining areas, crushers and waste dumps in dumping sites.

Each mining areas starts with ***Station*** module which denotes the entrance of the mining areas. This mining area includes the ***Process*** module that has a ***Resource*** in order to carry out the process of loading an empty truck. The exit point of the mining area will be completed by a ***Route*** module which sends the loaded truck to the specific destination. If the loaded truck carrying the material includes the valuable contains, it will send to the crushers and in case of containing the sterile material, the destination would be the waste dumps. Figure 3-1 shows the schematic picture of the mining area in the simulation model.

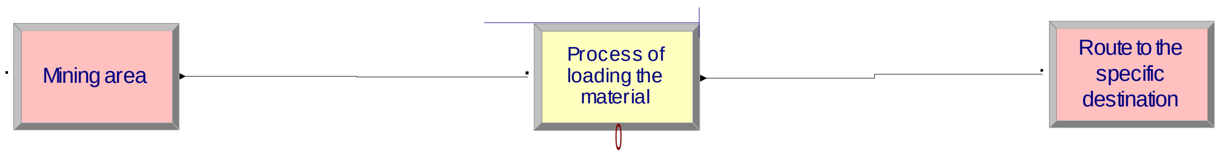

Figure 3- 1: Schematic picture of the mining area in simulation models

Each unloading area such as crusher or waste dumps starts with ***Station*** module. This unloading area includes the ***Process*** module that must utilize a ***Resource*** in order to complete the process of unloading a full truck. There are different kinds of logic for ***Resources*** in the ***Process*** at dumping sites. In crusher area, a crusher is added as a ***Resource*** which is based on ***seize, delay and release*** logic. In the waste dumps, the logic is only ***delay*** the ***Resource*** which is equal to the unloading time of each truck at these dumping sites. For example in this research, two trucks can unload in parallel in this area but crusher can only unload one truck at a time. This ***Process*** module will connect to the ***Decide*** module to choose the mining area where the empty truck will be sent based on the decision criterion which will be explained in the basic simulation model section. An ***Assign*** module is added after the decision part to allocate the desirable variables in this segment such as a counter to keep track of the number of sending trucks to the mining areas. The exit point of this area will be completed by a ***Route*** which sends the unloaded truck to the decided destination.

In this section, the general definition which we used in the simulation models was presented. Section 3.2.3 presents notations that are applied in simulation models.

3.2.3 Notations

The essential notations in the simulation models are presented.

Let first denote

n	Number of mining areas
m	Number of dumping sites

There are two different kinds of notations in this section such as ***Variable data*** and ***Attribute*** notations. Most of these notations are created in the ***Variable data*** module which is "measurement information" and subject to change and others is as ***Attribute data*** which stores entities information (Kelton et al., 2007).

Variable data

These parameters are mostly the input data which are constant and defined at the beginning of the simulation that would be presented in this section. The dynamic variables are shown in bold and italic forms and their value change during the simulation.

Constant variable

NO_k Number of available trucks for each type k

$VariableGoal\ (n, m, k)$ Number of trucks which has to be sent to the mining areas based on the optimal solution of the LP model, n rows represents the mining areas and m columns presents the dumping sites and k presents the type of truck

$Distance(n + m, n + m)$ Distances between mining areas and dumping sites which is the symmetric matrix by $n + m$ rows and $n + m$ columns

FTV_k The velocity of a full truck of type k

ETV_k The velocity of an empty truck of type k

$Shovelloadingtime(k)$ The loading time of trucks by shovels in mining areas

$Unloadingtime\ (k)$ The unloading time of trucks at dumping sites

Dynamic variables

$\boldsymbol{i}_{\boldsymbol{k}}$ A counter Variable to count the number of trucks at the beginning of the shift

$\boldsymbol{ALRST}(\boldsymbol{n},\boldsymbol{m},\boldsymbol{k})$ The number of trucks which are already sent from dumping sites to the mining areas during the simulation (a counter Variable)

Attribute data

The following attributes are added to model in order to store the entities information.

$TypeofTruck$ The type of truck

$NumberofTruck\ (k)$ A number assigned for each truck

All of the below expression will change and get new values during the simulation in order to complete the dispatching of trucks. As it was presented before, n is the number of mining areas, m is the number of dumping sites and k is the type of trucks.

$ALRSENT(n,m,k)$ A matrix with " n" rows and " $m \times k$ " columns which presents $\mathrm{ALTRSENT(i,j)} = \frac{\mathrm{ALRST(i,j)}}{\mathrm{VariableGoal(i,j)}}$ which is the comparison between the current number of already sent and the target (LP optimal solution)

$ALRSTEV(n,m,k)$ A matrix with " n" rows and " $m \times k$ " columns which presents $\mathrm{ALTRSENT(i,j)} = \frac{1+\mathrm{ALRST(i,j)}}{\mathrm{VariableGoal(i,j)}}$ which is comparison between the already sent and the target if we send an empty truck

$MinimumValue(m,k)$ The minimum value of each column of the $ALRST\#_{ij}(n,m,k)$ matrix

$SV(m,k)$ The mining area which has the $MinimumValue(m,k)$

$Done\ (n,m,k)$ A matrix with " n" rows and " $m \times k$ " columns which presents $ALRST_{ij}(i,j) = 1$

$Fin\ (m,k)$ Sum of the $Done\ (n, m \times k)$ for each mining area for example for mining area #1 is as follow:

$Done\ (1,1) + Done\ (1,2) + \cdots + Done\ (1, m \times k)$

In this section, the main notations which were applied in the simulation model were presented. In the above parameters and variables the necessary input data and calculation in order to simulate the haulage system behavior will be executed during the simulation. As it mentioned before the dynamic variables and all of expression notations will change and get new values during the simulation. The required input data are presented in Section 3.2.4.

3.2.4 Input data

The following information is the essential data that must be provided as inputs to run the LP and simulation models. These input data are the real data of an open pit mine which enter to models by the parameters which were explained in the previous sections.

- Tonnage of available material in front of each shovel
- Ore characteristics at each mining area
- Upper and lower bound of ore characteristics, needed for mixture of material in the crushers
- Loading time of shovels
- Unloading time at crushers and waste dumps
- Capacity and number of each type of truck
- Distances between mining areas and dumping sites
- The velocity of the full and empty for each type of truck
- Stripping ratio for waste removal in comparison to the total extracted material

3.3 Deterministic simulation models

This section presents two simulation models based on the deterministic input data. In the next subsection, we present the first model, called the basic simulation model, which is used to validate the result of the LP model.

3.3.1 Deterministic Basic simulation (DBS) model

The DBS model is developed to validate the optimal result of the LP model. In this regard, we developed the DBS model in Arena which takes into account the queue and waiting time at shovels and crushers and tries to send the similar number of trucks to different destinations based on the LP model result. The optimal solution of the LP model is considered as the target of this simulation model and defined at the beginning of the shift in the DBS model. In the DBS model, every time that an empty truck becomes available at dumping sites, a module checks the number of already sent of trucks (based on their type). The already sent number of trucks that is 2D variable will be compared with the target value. The mining area which has the minimum ratio of comparison is the area that we need to send the empty truck. This process will continue during the simulation in order to send as much as number of possible trucks to each mining area according to the predefined target.

This model has four main sections: Creation of entities, Crushers as parking lot and dumping sites, Mining areas (ore and waste), and Waste dumps as other options of dumping sites. These four parts are described below.

Creation of entities (initialization of model)

The creation of entities is done during steps 1 to 3 of the model at the beginning of the shift.

Step 1: Create different types of trucks "constantly" using the ***Create*** module.

Step 2: Connect the ***Create*** module to the ***Assign*** module. Add an attribute for $TypeofTruck$, ***Truck A*** and ***Truck B***. Assign variable i_k and increase this variable by one unit. This counter variable will be increased until it reaches the number of available trucks (NO_k) for each type k.

Step 3; The ***Route*** module sends all trucks to the crusher ***Station***. This step means that all the trucks are in the crusher at the beginning of the shift. Figure 3-1 shows the schematic picture of the entities creation in the simulation model.

Figure 3- 2: Schematic picture of the entities creation in simulation models

Crushers as parking lot and dumping sites

This section describes Step 4 to 6 of the model. Figure 3-3 shows the schematic picture of the crusher area in the simulation model.

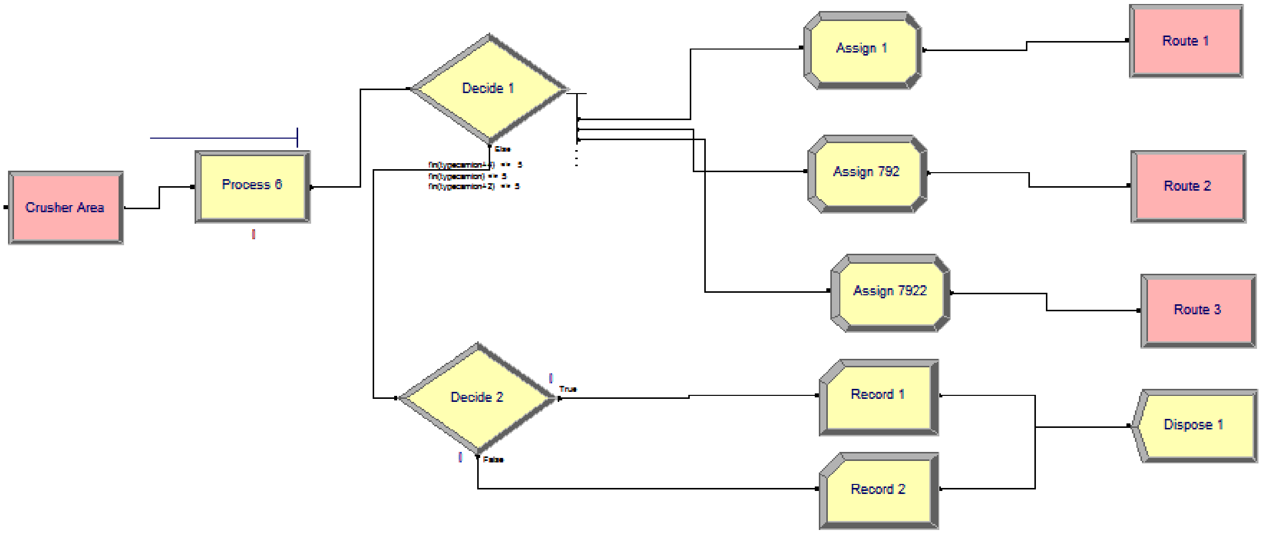

Figure 3- 3: Schematic picture of the crusher area in simulation models

At the beginning of the shift all of the trucks are empty and located at the crusher. They will be sent to the mining areas based on the decision measure that will be explained in **Step 4**. Otherwise, the full truck that comes to the crusher will stay in the queue until the crusher becomes free and available.

Step 4: Choose the truck's destination in the ***Decision*** module. At the beginning of the shift and during the shift after unloading the material in the crushers' areas, we need to decide to which area we should send the empty truck. This decision is based on the following formula:

$$Fin\ (m \times k) <> n \tag{3.39}$$

If the above expressing is true then the empty truck will be sent to the mining area which has the $MinimumValue(1, m \times k)$, and if not the empty trucks will be disposed of the simulation system.

Step 5: Increase the $ALRST(i, j)$ by one unit as follows:

$$ALRST(i,j) = ALRST(i,j) + 1 \quad (3.40)$$

Step 6: Send back the empty truck to the selected mining area. The required time is equal to the following formula:

$$\text{Rout Time of an empty truck} = \frac{Distance\ (\text{crusher, selected mining area})}{ETV_k}$$

Mining areas (ore and waste)

This section describes the mining areas in an open pit mine where shovels are distributed to extract the material and load the empty trucks. This section starts at Step 7 and terminates at Step 8. An empty truck waits in the mining area until to be served by shovel. The required time to load an empty truck is equal to the loading time at each shovel.

Step 7: If the truck is full of ore, send it to the crusher; otherwise send it to the waste dumps.

Step 8: Calculate the time taken for a full truck to reach the dumping destination using the following formula:

$$\text{Rout Time of a full truck} = \frac{Distance\ (\text{mining area, dumping sites})}{FTV_k}$$

Figure 3-4 shows the schematic picture of the mining areas in the simulation model.

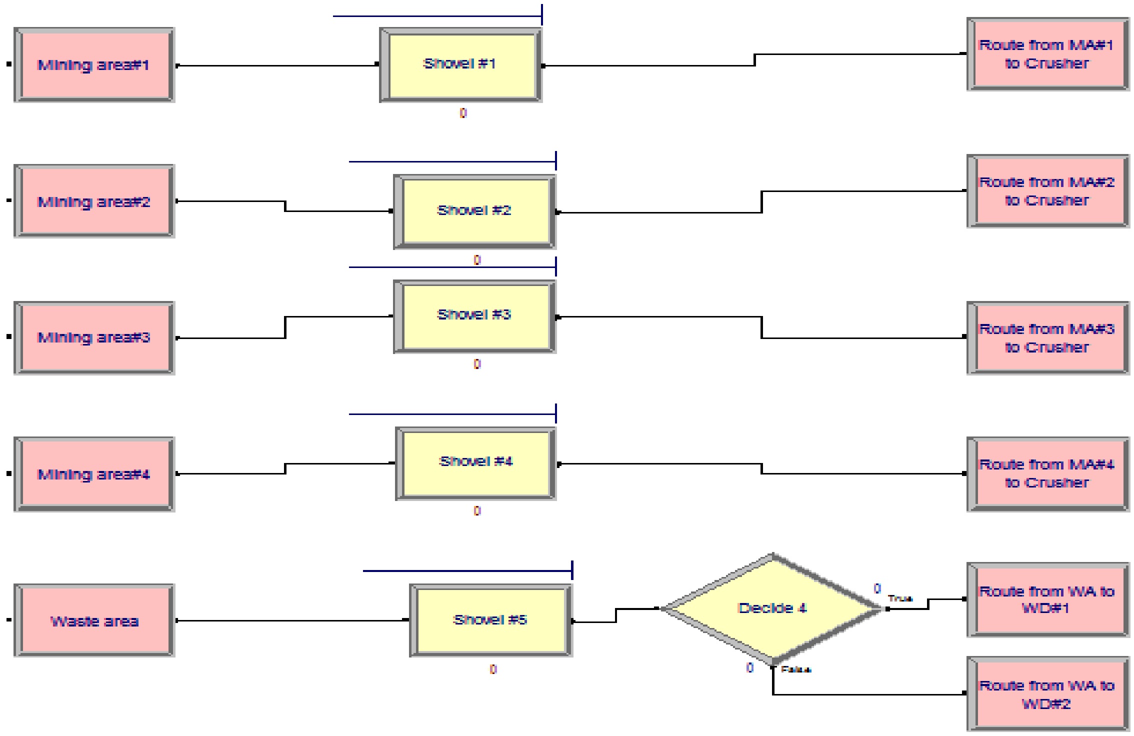

Figure 3- 4: Schematic picture of the mining areas in simulation models

Waste dumps as other options of dumping sites

The same procedure for choosing the preferable mining area will be applied for a full truck in waste dumping in order to send back the empty truck to the mining areas. The only difference between this dumping site and crushers is that in this research there is an opportunity for full trucks to be unloaded in parallel in these sites. The required time for unloading is equal to the unloading time at waste dumps based on the type of trucks. Figure 3-5 shows the schematic picture of the dumping site in the simulation model.

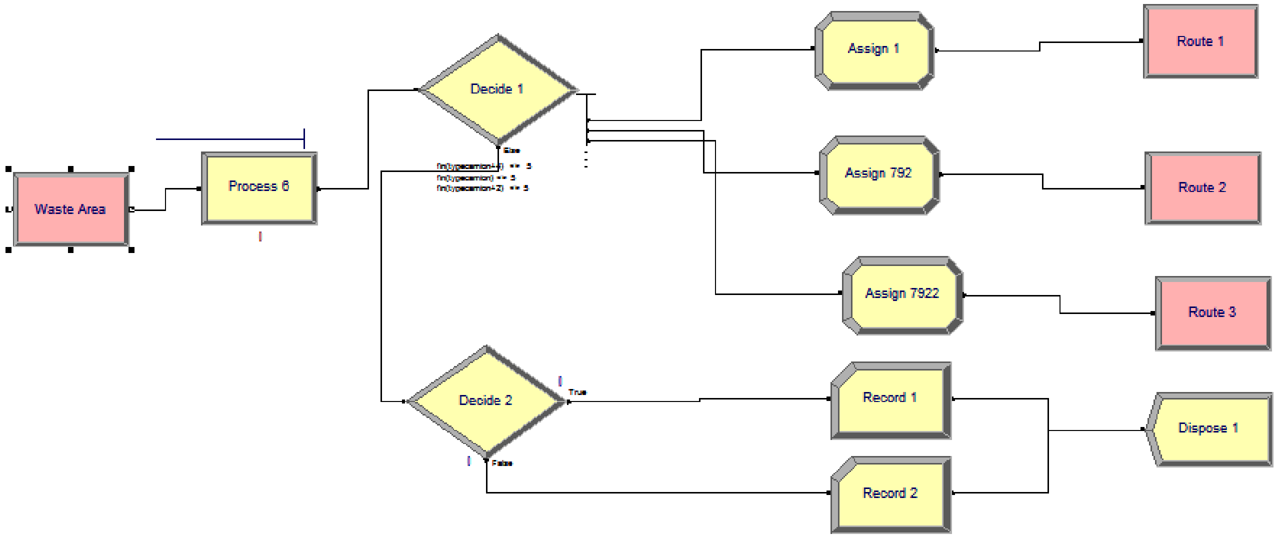

Figure 3- 5: Schematic picture of the dumping site in simulation models

In the next section, the possibility of finding a new ways of production planning for an open pit mine for a very short term period would be tested by developing the real time simulation model.

3.3.2 Deterministic Real Time simulation (DRTS) model

The DRTS model maximizes ore production by considering the LP model constraints such as blending and stripping ratio. This model maximizes the ore production, which is given by the number of trips between the mining area and crushers, while considering the constraints. In this model, all of the requirements in terms of the blending constraints, the ore characteristics at each mining area, the stripping ratio, the total available material in front of each shovel, etc., are entered into the model. Every time that an empty truck becomes available, the simulator calculates the decision measure that considers the constraints of the LP model. The simulator tries to send the truck to the mining area which has the minimum catastrophe and respects the constraints. There are coefficients to penalize the direction which is not respecting the essential requirements. At the end of the simulation, all the constraints are respected.

The output presents: 1- the total tonnage of ore and waste, 2- the number of trucks that where sent to the mining areas from each of the dumping sites (crushers or waste dumps).

In order to develop the DRTS model, we require new definitions in dumping sites and also new notations. In this model, we have the similar definitions for creation of ***Entities*** and mining areas but there is a different definition for dumping sites after the ***Process*** module.

The ***Process*** module will connect to the ***Assign*** module at each dumping site to allocate different variables which are defined below. All decisions to select to which mining area we are sending the empty truck are taken by the ***Expression*** module in ***Advanced Process*** panel. After decision is taken a ***Route*** module sends the unloaded truck to the decided destination.

Let define:

l Number of ore characteristic

p Number of constraints

These parameters are also the input data which are constant and defined at the beginning of the simulation. There are dynamic variables which are assigned in the ***Assign*** module during the simulation run. These variables are shown in bold and italic format in the following part. The rest of the notations are the parameter which remains constant during the simulation.

Constant parameters

$\mathrm{OreCh}_l\ (\mathrm{n})$ The ore characteristics in mining areas

$\text{blending requirement}(l)$ The minimum or maximum required quantity of the ore characteristics in ore at the end of the shift in crusher

$Tonnage\ of\ material\ (n)$ The total material which is available in front of each shovel

$Ni(n)$ This parameter presents the number of truck waiting at shovel and traveling to shovel multiply by loading time at shovel has to be less than route time from dumping site to shovel and if not it will be waiting time at shovels.

$OreRatio$ This parameter is equal to $1 - R_{min}$

Dynamic variables

$\boldsymbol{TQM\ (t)}$ The total quantity of ore and waste extracted and transported by trucks to their destinations

$\boldsymbol{ALRTQA(n)}$ The quantity of material already extracted by shovels in mining areas during the simulation

$\boldsymbol{TotalOre\ (t)}$ The cumulative variable that shows the amount of ore extracted during the simulation

$\mathbf{ALROreCh_l}(\boldsymbol{t})$ The amount of the $\mathrm{OreCh_l}$ in the $\mathrm{TotalOre}$

$\boldsymbol{k(p)}$ The penalty for not respecting the constraints at the mining area

$\boldsymbol{NO(t)}$ The number of trucks sent to the mining areas from crushers or waste dumps (a 2D counter Variable)

$\boldsymbol{ObjetiveFunction\ (n, m, k)}$ A matrix with " n" rows and " $m \times k$ " columns that presents the decision measure that is presented in (3.41)

$\boldsymbol{Minimumcatastrophe}$ The minimum value of $ObjetiveFunction\ (n, m, k)$

Selection The mining area that has the $Minimumcatastrophe$

The DRTS simulation has the following differences in selecting criterion. As we discussed previously, a different criterion will allow the simulator to select the empty truck destinations. This decision is based on the blending constraint, the available quantity of material in front of each shovel in mining areas. The allowable number of trucks which transferring to shovel and the number of trucks in queue at each shovel that has to be less than time route (from dumping site to mining area) divided by shovel loading time. The final constraint is the stripping ratio constraint that presents the amount of the extracted waste out of the total extracted material during the simulation.

For each of these constraints, a penalty is considered in order to penalize the new destination that is not respecting the required constraints. The following formula is to evaluate the level of violation of each constraint in order to select the destination for an empty truck. It is necessary to mention that the following formula is evaluated for each mining area.

$$
\begin{aligned}
&\mathrm{k(1).MX}\left(0,\left(\text{blending requirement}(1)-\left(\left(\mathrm{ALROreCh1(t)}+\mathrm{CA_k}.\,\mathrm{OreCh1}\ (1,1)\right)\big/_{\left(\mathrm{TotalOre(t)}+\mathrm{CA_k}\right)}\right)\right)\right)\\
&+\mathrm{k(2).MX}\left(0,\left(\left(\left(\mathrm{ALROreCh2(t)}+\mathrm{CA_k}.\,\mathrm{OreCh2}\ (1,1)\right)\big/_{\left(\mathrm{TotalOre(t)}+\mathrm{CA_k}\right)}\right)-\text{blending requirement}(2)\right)\right)\\
&+\mathrm{k(3).MX}\left(0,\left(\left(\left(\left(\mathrm{NE}(\text{mining area}_1)\right)+\mathrm{NQ}(\mathrm{Shovel_1.\,Queue})\right)\big/_{\mathrm{Ni(1)}}\right)-1\right)\right)\\
&+\mathrm{k(4).MX}\left(0,\left(\left(\left(\mathrm{ALRTQA(1)}+\mathrm{CA_k}\right)\big/_{\text{Tonnage of material }(1,1)}\right)-1\right)\right)\\
&+\mathrm{k(5).MX}\left(0,\left(\left(\left(\mathrm{TotalOre(t)}+\mathrm{CA_k}\right)\big/_{\left(\mathrm{TQM(t)}+\mathrm{CA_k}\right)}\right)-\mathrm{OreRatio}\right)\right)
\end{aligned}
\tag{3.41}
$$

In this formula, the first part is related to the blending constraints that we want to have at least that specific amount of blending requirement. Also, the second part is when we want to have at most that amount of the blending requirement. The third part is related to considering the traffic in simulation model by using the output of the simulation such as number of transferring truck to the specific mining area and the number in queue at shovel in this mining area. The forth part considers the quantity of material which is available at each mining area during the shift. And finally the last part presents the stripping ratio in an open pit mine.

After the ***Process*** module the process goes through an ***Assign*** module which will add the following variables:

1. TQM which is the total extarcetd material (ore and waste) and increase it by capacity of the truck by considering the type of truck as following calculation

$$TQM(t) = TQM(t) + CA_k \tag{3.42}$$

2. $ALR\mathrm{OreCh}_l(t)$ which is the amount of the ore characteristic in the total ore and increase it by capacity of the truck multiply by the amount of the $\mathrm{OreCh}_l(1, i)$ of the material at mining area as follows:

$$ALR\mathrm{OreCh}_l(t) = ALR\mathrm{OreCh}_l(t) + CA_k \,.\, OreCh_l\,(1, i) \tag{3.43}$$

3. $\mathrm{ALRTQA}(i)$ that is the already extracted material by shovel at mining areas and increase by the capacity of the truck when an empty truck is sent to the new mining area

$$\mathrm{ALRTQA(i)} = \mathrm{ALRTQA}(i) + CA_k \tag{3.44}$$

4. $\mathrm{TotalOre}$ that presents the amount of ore and is the result of the following formula

$$\mathrm{TotalOre\ (t)} = \mathrm{TQM(t)} - \mathrm{ALRTQA\ (i)} \tag{3.45}$$

5. Increase the variable $\mathrm{NO}\,(\mathrm{n}, \mathrm{m}, \mathrm{k})$ by one unit. This variable is counter to keep track of the already sent of trucks type k from each dumping site to each mining area

$$\mathrm{NO}\ (\mathrm{i}, \mathrm{j}) = \mathrm{NO}(\mathrm{i}, \mathrm{j}) + 1 \tag{3.46}$$

The next section presents the essential modification in both simulation models in order to develop the stochastic model which is more accurate and reflects the reality of the problem in an open pit mine.

3.3.3 Stochastic models

Since deterministic models do not consider the uncertainties in the simulation models, they cannot be the best choice to validate and analyze the result, in this subsection, simulation models are improved by accumulating the uncertainties to the simulation models.

These uncertainties are related to the following areas:

a. Loading time by shovels at each mining area. This loading time is the required time to load the truck by shovels which are located in the mining areas.

b. Velocity of the full and empty trucks during transporting material from mining areas to the destinations and returning from the unloading areas to the mining areas.

c. Unloading time at crushers and waste dumps. This time is the required time to unload the truck in the crushers or waste dumps.

3.4 summary

In this chapter we have described the LP and simulation models, and then in the next chapter we will test these models in order to evaluate their strength and weakness in an open pit mine.

CHAPTER 4: TESTS, RESULTS AND ANALYSIS

The LP model and the simulation models that have been developed in Chapter 3 are applied on a real mine using Excel Solver (Microsoft office, 2010) and Arena simulation software (Rockwell Automation, 2012) respectively.

The LP model that is to maximize the total ore production during the shift uses Solver to find the number of trips between mining areas and waste dumps. Then, the final result of the LP model is considered as the target of the DBS model while considering the waiting times at servers. The objective of this model as explained in the previous chapters is to validate the result of the LP model and to provide an operational dispatching plan for the open pit mine. In this regard, the result of the DBS model will be compared to the result of the LP model. Moreover, a new method of VSTPP is developed in chapter 3 which is called DRTS model and employs Arena simulator. In addition, the solution of this model will be compared to the solution of the LP model with the purpose of verifying the developed simulation model and validating the LP model. At the end of this chapter, the performance of the LP model and simulation models considering the different states as the bottleneck of operational system will be discussed.

The next section presents all of the required input data of the mine studied in this work.

4.1 Instances

The open pit mine under study is a coal mine with five mining areas where shovels are distributed in these areas. Four of these mining areas are located in the valuable mineral (ore) area (shovel #1 to shovel#4 are distributed in these areas) and the other one is in the waste area (shovel #5). There are two types of trucks with different capacities and velocities. Loaded trucks will be traveled to transfer the extracted material to the destinations including one crusher and two waste dumps. The following sections, presents the essential input data which are constant at the beginning and during the simulation:

- Tonnage of available material in front of each shovel
- Ore characteristics in mining areas
- The essential upper and lower bounds of ore characteristics in crusher
- Loading and unloading time of trucks

- Number and capacity of trucks
- Distance between mining areas and dumping sites
- The velocity of full and empty trucks
- Stripping ratio

4.1.1 Tonnage of available material in front of each shovel

There are limited amount of material in front of each shovel in these five mining areas at the beginning of the shift. The maximum amount of material in front of each shovel in mining areas is shown in the following table. However, there is no restriction for capacity of crusher and waste dumps in this case.

Table 4.1 shows the quantity of available material in front of each shovel in the mining areas.

Table 4.1: Available material in front of each shovel in mining areas

Mining areas	Shovel #1	Shovel #2	Shovel #3	Shovel #4	Shovel #5
Available material in front of each shovel (ton)	111,000	130,000	90,000	45,000	120,000

4.1.2 Ore characteristics in mining areas

In this case, there are three main ore specifications which have to be considered as blending constraints in combination of the total ore in the crusher. The mixture of these specifications is required for sending the output of the crusher to the processing plant in the mine. The ore characteristics in each mining area which include BTU, sulfur and ashes are shown in table 4.2.

Table 4.2: Ore characteristics in each mining area

Ore characteristics	Shovel #1	Shovel #2	Shovel #3	Shovel #4	Shovel #5
BTU (kbtu/ton)	12	13	17.7	12.9	-
Sulfur (%)	1.2	2.5	2.5	2.4	-
Ashes (%)	21	11	19	12	-

As it can be seen from the table, there are no predefined specifications for the material in front of the shovel#5 since the loaded truck in this area will transfer the material to a waste dump.

4.1.3 Upper and lower bounds of ore characteristics at the crusher

In this section, the desired upper and lower bounds of the ore characteristics at the crusher are presented. As shown in Table 4.3, the amount of ore sent to the crusher must content at least 12.7% of kBTU. The impurities, sulfur and ash levels, which have to be controlled at maximum 2.2 % and 14% percent, respectively. Table 4.3 presents the upper and lower bounds on the ore characteristics.

Table 4.3: Upper and lower bounds on some ore characteristics

Ore grades	lower bounds	Upper bounds
BTU (kbtu/ton)	-	12.7
Sulfur (%)	2.2	-
Ash (%)	14	-

4.1.4 Loading and unloading time of trucks

This section presents the shovel loading time to load an empty truck in mining area and the unloading time of full truck in the dumping sites (crusher and waste dumps). The table 4.4 indicates the shovel loading time in mining areas for two types of truck. According to this table there is different loading time for two types of trucks but it is similar for each type of truck in different shovels.

Table 4.4: Shovel loading time in mining areas

Shovel loading time (seconds)					
Type of the truck	Shovel #1	Shovel #2	Shovel #3	Shovel #4	Shovel #5
Truck type ***A***	250	250	250	250	250
Truck type ***B***	300	300	300	300	300

Table 4.5 presents the unloading time of the full trucks for two types of truck in dumping sites (crusher and waste dumps).

Table 4.5: Unloading time in dumping sites

Unloading time (seconds)			
Type of the truck	Crusher	Waste dump #1	Waste dump #2
Truck type ***A***	120	105	90
Truck type ***B***	145	125	110

4.1.5 Number and capacity of trucks

Table 4.6 displays the available number of trucks in the mine and also the capacity of each type of truck.

Table 4.6: Number and capacity of each type of truck

Type of the truck	Number of each truck	Capacity of each truck (ton)
Truck type ***A***	8	200
Truck type ***B***	16	250

4.1.6 Distance between mining areas and dumping sites

As there are five mining areas and three unloading areas, it is required to determine the distance between all of these areas. Table 4.7 presents the related distance between loading and unloading areas. As it can be seen from the table, there is no possibility of mobility between two unloading areas or two loading areas. Also, trucks from the four mining areas which are located in the ore area are only allowed to travel to the crusher and the loaded truck from the waste area can travel either to the waste dump #1 or waste dump #2.

Table 4.7: Distance between mining areas and dumping sites

Distance (meter)								
to / From	Waste dump #1	Waste dump #2	Crusher	Shovel #1	Shovel #2	Shovel #3	Shovel #4	Shovel #5
Waste dump#1	0	-	-	10275	8905	6850	6850	8879
Waste dump #2	-	0	-	10960	11782	5480	8220	6181
Crusher	-	-	0	9216	11239	6181	6519	8220
Shovel #1	-	-	8200	0	-	-	-	-
Shovel #2	-	-	10000	-	0	-	-	-
Shovel #3	-	-	5500	-	-	0	-	-
Shovel #4	-	-	5800	-	-	-	0	-
Shovel #5	10823	7535	-	-	-	-	-	0

4.1.7 The velocity of full and empty trucks

Table 4.8 specifies the velocity of full trucks and empty trucks for each type of truck.

Table 4.8: Velocity of each type of truck

Type of the truck	full truck(m/s)	Empty truck (m/s)
Truck type ***A***	13.7	16.7
Truck type ***B***	15	18

4.1.8 Stripping ratio

The final input data in this part is the stripping ratio. The volume of the extracted waste to the total extracted material during the shift should be at least 20 percent as it is shown in the following formula:

$$\frac{Total\ extarcted\ waste\ at\ the\ end\ of\ the\ shift}{Total\ extarcetd\ material\ at\ the\ end\ of\ the\ shift} \geq 0.2$$

In the next section, first of all the result of the LP model and afterward the comparison of the DBS and DTRS models with LP model will be discussed.

4.2 Comparing the deterministic model result for DBS and DRTS with LP model

A detailed description of the LP model results, the supporting data and an analysis of how the model behaves along with the comparison with other models are given below.

4.2.1 The optimal solution of the LP model

The optimal solution of the LP model using Solver for a shift of 12 hours is presented in the following tables. The tonnage of extracted ore and waste is presented in Table 4.9. According to this table, the tonnage of the ore extracted and transported to the crusher is 74,400 tons per shift using the 8 trucks type ***A*** and 16 trucks type ***B*** during the 12 hours shift. Also, the tonnage of the waste is 34,400 ton per shift which is about 32 percent of the total extracted material.

Table 4.9: Tonnage of extracted ore and waste per shift

Amount of extracted material (ton)	LP Optimal result
Ore	74,400
Waste	34,400

The LP model also determines the number of trips between mining areas and dumping sites. In the following tables, first, the numbers of empty trucks that have been sent from the unloading areas to the mining areas and then, the number of full trucks from mining areas to the dumping sites will be presented. Table 4.10 shows the number of empty trucks form each of the unloading areas to the mining areas for type ***A*** trucks.

Table 4.10: Number of empty trucks type ***A*** – in the LP solution

Truck type ***A***-Empty						Total number
From \ to	Shovel #1	Shovel #2	Shovel #3	Shovel #4	Shovel #5	
Waste dump#1	0	0	12	0	160	172
Waste dump #2	0	0	0	0	0	0
Crusher	0	0	0	0	12	12
Total number	0	0	12	0	172	184

As it can be seen in this table, the total number of trips of truck type ***A*** is 184 in one shift. According to this table no empty truck has been sent to shovels 1, 2 and 4 and no full truck of type ***A*** has been sent to the waste dump #2.

Table 4.11 presents similar information for type ***B*** trucks.

Table 4.11: Number of empty trucks of type ***B*** – in the LP solution

Truck type ***B***-Empty						Total number
From \ to	Shovel #1	Shovel #2	Shovel #3	Shovel #4	Shovel #5	
Waste dump#1	0	0	0	0	0	0
Waste dump #2	0	0	0	0	0	0
Crusher	58	77	11	142	0	288
Total number	58	77	11	142	0	288

According to the above table, the total number of trips for truck type ***B*** is 288 in one shift.

Table 4.12 indicates the number of full trucks form each of the mining areas to the unloading areas for type ***A*** trucks.

Table 4.12: Number of full trucks of type ***A***– in the LP solution

Truck type ***A***-full				Total number
From \ to	Waste dump #1	Waste dump #2	Crusher	
Shovel #1	0	0	0	0
Shovel #2	0	0	0	0
Shovel #3	0	0	12	12
Shovel #4	0	0	0	0
Shovel #5	172	0	0	172
Total number	172	0	12	184

Table 4.13 presents the number of full trucks form each of the mining area to the unloading areas for type ***B*** trucks.

Table 4.13: Number of full trucks type ***B***– in the LP solution

Truck type ***B***-full				Total number
From \ to	Waste dump #1	Waste dump #2	Crusher	
Shovel #1	0	0	58	58
Shovel #2	0	0	77	77
Shovel #3	0	0	11	11
Shovel #4	0	0	142	142
Shovel #5	0	0	0	0
Total number	0	0	288	288

According to the solution of the LP model, all of the type ***B*** trucks have been sent to the mining areas and no truck type ***B*** has been sent to the waste area. The LP solver uses trucks of type ***B***, which has a bigger capacity than truck ***A***, in the mining areas that include ore material. The reason is to maximize the number of trucks which have been sent to the ore areas while considering the blending constraints.

As it can be seen from the above tables, the optimal solution of LP model has often extreme solution. For instance, only trucks type ***A*** are sent to the waste areas and trucks type ***B*** are sent to the mining areas which include ore material. Moreover, the quantity of waste that has been removed is 32% instead of 20% (of the total extracted material) indicating the difficulties to extract more ore because of the blending constraint to satisfy. As mentioned before, the next section presents the result of the DBS model using the Arena software in order to compare with the result of the LP model.

4.2.2 Comparing the results of the LP model with DBS model

The LP model presented in the previous section is not influenced by the waiting time at shovels and server in the mine. Also, This LP model does not present how to dispatch trucks to shovels in mines.

Using the DBS model, we want to know if ignoring the waiting time at servers has an impact on the real productivity of the mine. The results of the LP model which was shown in Tables 4.10 and 4.11 have been entered into the $VariableGoal\,(n, m, k)$ matrix. Table 4.14 shows the $VariableGoal\,(n, m, k)$ matrix. The first column in this matrix is related to the number of empty trucks which have been sent from the waste dump #1 to the mining areas for type ***A*** and column two is the number of empty trucks for type ***B***. The third and fourth columns are related to the waste dump #2 for trucks of type ***A*** and ***B***, respectively. Finally, the last two columns are related to the number of empty trucks from the crusher to the mining areas.

Table 4.14: $VariableGoal\,(n, m, k)$

to / From	Waste dump #1		Waste dump #2		Crusher	
	Type A	Type B	Type A	Type B	Type A	Type B
Shovel #1	x	x	x	x	x	x
Shovel #2	x	x	x	x	x	x
Shovel #3	x	x	x	x	x	x
Shovel #4	x	x	x	x	x	x
Shovel #5	x	x	x	x	x	x

The essential inputs have been entered into the DBS model and this model has been run using the Arena software. During the simulation, every time when an empty truck reaches to the decision part in this model, the number of sent trucks from each unloading areas is compared by the related target in the $\text{VariableGoal}(n, m, k)$ matrix. The destination being the latest on its production target is selected. This process will be continued until the end of the simulation or when the entire target is achieved.

Table 4.15 presents the results of the LP model along with the DBS model for 12 hours shift for this instance.

Table 4.15: Results of the LP and DBS models

Quantity of extracted material (ton)	LP model result	DBS model
Ore	74,400	72,900
Waste	34,400	34,400

In our test it was impossible to reach the same production level as the one obtained by LP model. As it is mentioned in Chapter 3, the crusher is considered as the parking lot at the beginning of the shift. This means that at the beginning of the shift, all of the trucks are empty and will be sent to the different destinations. The simulation model loses some time that is the sum of the service time at crusher and traveling time from the crusher to the mining areas for all of these trucks. This will affect the final result of the DBS model which is smaller than LP optimal solution. For example, on the one hand, the average traveling time and service time at crusher for type ***B*** trucks is 659 seconds that is 0.02 percent of the 12 hours shift. On the other hand, the difference between ore production of these models is 0.02. Consequently, the DBS model outcomes validate the results of the LP model.

Tables 4.16 and 4.17 display the results of the DBS model as the total number of empty trucks sent from the unloading areas to the mining areas.

Table 4.16: Number of empty trucks type ***A***- in the DBS model solution

Truck type ***A***-Empty						Total number
From \ to	Shovel #1	Shovel #2	Shovel #3	Shovel #4	Shovel #5	
Waste dump#1	0	0	12	0	160	172
Waste dump #2	0	0	0	0	0	0
Crusher	0	0	0	0	12	12

Truck type ***A***-Empty						Total number
From \ to	Shovel #1	Shovel #2	Shovel #3	Shovel #4	Shovel #5	
Total number	0	0	12	0	172	184

Table 4.17 presents the total number of trucks trip in the DBS model for trucks type ***B***.

Table 4.17: Number of empty trucks type ***B***- in the DBS model solution

Truck type ***B***-Empty						Total number
From \ to	Shovel #1	Shovel #2	Shovel #3	Shovel #4	Shovel #5	
Waste dump#1	0	0	0	0	0	0
Waste dump #2	0	0	0	0	0	0
Crusher	57	75	10	140	0	282
Total number	57	75	10	140	0	282

As it can be seen from the above tables and also the amount of extracted wastes, the DBS model has been able to send all empty trucks from the unloading areas to the mining areas which were determined by the LP model. However, for trucks type ***B*** that has been transferring between crusher and mining areas, all desired targets have not been achieved. Not achieving the targets for type ***B*** results in the smaller amount of the ore in comparison with the LP model result.

Although the proposed simulation model (DBS) is capable of replicating the LP model but it is not a good representation of the reality. Therefore, in the next section we will use another simulation model which will simulate haulage system in the open pit mine considering all of the required constraints. Also, the result of this model (DRTS) will be compared with LP optimal solution.

4.2.3 Comparing the results of the LP model with DRTS model

The objective of the DRTS model, which has been described in Chapter 3, is to find a new method for real time dispatching system in an open pit mine for a very short-term period. The DRTS model has been run for the 12 hours shift using the same inputs for the LP and DBS models.

Table 4.18 indicates the LP and DRTS results in terms of the ore and waste production. According to this table, tonnage of the ore is 72,500 ton per shift and the waste is 18,750 ton per shift. Therefore, the tonnage of the extracted waste in comparison with the LP model is decreased to 21%. This model reduces the production of waste for about 45 percent in comparison with the LP model whilst considering the stripping ratio in the mine which will significantly reduce the transportation cost in the mine. This simulation model overcomes the extreme result of the LP model and presents a smooth dispatching plan for haulage system.

Table 4.18: Results of the LP and DRTS models

Quantity of extracted material (ton)	LP model result	DRTS model
Ore	74,400	72,500
Waste	34,400	18,750

Table 4.19 and 4.20 show the results of the DRTS model for the final number of empty trucks which have been sent from the unloading areas to the mining areas.

Table 4.19: Number of empty trucks type ***A***- in the DRTS model solution

Truck type ***A***-Empty						Total number
From \ to	Shovel #1	Shovel #2	Shovel #3	Shovel #4	Shovel #5	
Waste dump#1	1	2	1	4	9	17
Waste dump #2	0	6	0	2	4	12
Crusher	23	19	5	42	17	106
Total number	24	27	6	48	30	135

The total number of truck trips of the DRTS model for type ***B*** trucks is shown in table 4.20.

Table 4.20: Number of empty trucks type ***B***- in the DRTS model solution

Truck type ***B***-Empty						Total number
From \ to	Shovel #1	Shovel #2	Shovel #3	Shovel #4	Shovel #5	
Waste dump#1	2	2	2	6	8	20
Waste dump #2	3	10	1	9	4	27
Crusher	32	40	13	86	39	210
Total number	37	52	16	101	51	257

According to the above tables, the DRTS model presents a smooth dispatching plan for truck and shovel hauling system in the open pit mine. The reason is the set of constraints which were defined in this model and the objective of the DRTS model in order to provide a new way of VSTPP for the open pit mine.

Results of the LP model and two other discussed simulation models have been presented in this section. In the next section, two other models called Stochastic Basic Simulation (SBS) and Stochastic Real Time Simulation (SRTS) will be discussed and then compared to the LP model.

4.3 Comparing the results of Stochastic Basic Simulation (SBS) and Stochastic Real Time Simulation (SRTS) model with LP model

Although, the simulation models have been used to resemble an actual situation in an open pit mine, considering the probabilities and uncertainties dictated by the reality is still required to improve the simulation models and subsequently achieve better result for the VSTPP. To modify the deterministic simulation model to a stochastic simulation model it is required to use the randomness input data in simulation models. The stochastic simulation models consider the uncertainties of the problem related to the trucks and shovels operation systems such as the loading and unloading time for trucks and the velocity of the full and empty trucks.

In order to change the deterministic variables to the stochastic variables, a triangular density function is used. This function is the one normally used in the literature. Three coefficients are considered. These coefficients will be multiplied by the deterministic value of the loading and unloading time and the velocity of trucks. In order to have the same mean for the triangular distribution by the deterministic value, the sum of these coefficients must be equal to 3. The reason is that in the triangular distribution, mean is equal to the following formula:

$$\frac{\alpha_1 \times a + \alpha_2 \times a + \alpha_3 \times a}{3}$$

a: The deterministic value

Table 4.21 shows the value of these coefficients.

Table 4.21: Coefficients for triangular distribution

Coefficients	α_1	α_2	α_3
Value	0.2	0.8	2

Table 4.22 presents the random variables and their probability density functions for the stochastic simulation models.

Table 4.22: Random variables and their probability density functions

Random Variable	Probability Density Function
Loading Time at each shovel (seconds)-Type ***A***	Triangular (50, 200, 500)
Loading Time at each shovel (seconds)-Type ***B***	Triangular (60, 240, 600)
Full Truck Velocity during the Shift-Type ***A***	Triangular (2.74, 10.96, 27.4)
Full Truck Velocity during the Shift-Type ***B***	Triangular (3, 12, 30)
Empty Truck Velocity during the Shift-Type ***A***	Triangular (3.34, 13.36, 33.4)
Empty Truck Velocity during the Shift-Type ***A***	Triangular (3.6, 14.4, 36)
Unloading Time at crusher (seconds)- Type ***A***	Triangular (24, 96, 240)
Unloading Time at crusher (seconds)- Type ***B***	Triangular (29, 116, 290)
Unloading Time at waste dump#1 (seconds)-Type ***A***	Triangular (21, 84, 210)
Unloading Time at waste dump#1 (seconds)-Type ***B***	Triangular (25, 100, 250)
Unloading Time at waste dump#2 (seconds)- Type ***A***	Triangular (18, 72, 180)
Unloading Time at waste dump#2 (seconds)-Type ***B***	Triangular (22, 88, 220)

In the next section, the results obtained by the LP, the DBS and the SBS models will be compared.

4.3.1 Comparing the results of the LP, DBS and SBS models

In this section, the SBS model results will be compared with the results of the DBS and LP models. The SBS model has been run in the Arena for 100 replications and 12 hour shift. It is worth mentioning the following results are the average of the tonnage of ore and waste for these 100 replications.

Table 4.23 presents the quantity of extracted material of the LP, DBS and SBS models. As it can be seen from the table, the average tonnage of the ore obtained by the SBS model is less than the one obtained by both the DBS and the LP models. Since the SBS model considered the uncertainties in loading and unloading time and the velocity of trucks so it is more close to the real situation in the mine.

Table 4.23: Result of the LP, DBS and SBS models

Quantity of extracted material (ton)	LP model result	DBS model	SBS model*
Ore	74,400	72,900	71,625.5
Waste	34,400	34,400	33,812

* Average amount of 100 replications

Table 4.24 presents the waiting time at crusher and shovels in SBS model for 100 replications in Arena simulation software. In the next table and the following tables of this chapter the average column indicates the average value of each result over 100 replications. Half width returns the 95% confidence interval around the mean value of each result. The third and fourth column return the minimum and maximum value recorded of each result across all replications run so far. The last column specifies the maximum value of each result during 100 replications (Kelton et al., 2007).

According to this table, the average waiting times for 100 replications at crusher, shovel #4 and shovel #5 are between 7 to 10 minutes. According to the optimal result of the LP model, these shovels are located in the mining areas with the highest number of trips during the shift. Since, the SBS model is based on the optimal solution of the LP model and follows it as a target, the result of the following tables show the longest waiting times at these shovels and crusher.

Table 4.24: Waiting time at servers in the SBS model

Waiting time (seconds)					
Description	average	Half width	Minimum average	Maximum average	Maximum value
Crusher	598	16.38	411	780.3	3832
Shovel #1	13.5	1.39	0.6	37	484.2
Shovel #2	47.8	2.56	19.3	81	742
Shovel #3	15	2.28	0	56	493
Shovel #4	517	34.31	210	1071	2425
Shovel #5	458	9.85	347	574.6	1743

Table 4.25 shows the shovels and crusher utilization for 100 replications in Arena simulation software. Since the average waiting times at crusher, shovel #4 and shovel #5 is the longest waiting times among the other servers, the utilization of these servers have also been the maximum utilization during the shift. In average, the crusher was working for about 99 percent of the time and this number for shovel #5 and shovel #4 is 96 and 92 percent respectively.

Table 4.25: Utilization of servers in the SBS model

Utilization of servers (percent)			
Description	average	Minimum average	Maximum average
Crusher	0.99	0.94	1
Shovel #1	0.38	0.32	0.43
Shovel #2	0.51	0.46	0.57
Shovel #3	0.13	0.1	0.17
Shovel #4	0.92	0.86	0.96
Shovel #5	0.96	0.92	0.98

In the previous section, the uncertainties are added into the basic simulation model. In the next section, the result of the LP model, DRTS and SRTS model will be compared.

4.3.2 Comparing the results of the LP, the DRTS and the SRTS models

The SRTS model has been run in the Arena for 100 replications and 12 hours shift. Table 4.26 shows results of the LP, DRTS and SRTS models.

Table 4.26: Results of the LP, the DRTS and the SRTS models

Quantity of extracted material (ton)	LP model result	DRTS model	SRTS model*
Ore	74,400	72,500	73,015.5
Waste	34,400	18,750	18,639.5

* Average amount of 100 replications

According to this table, the average amount of the production of ore is 73,015.5 tons per shift which is less than the amount of tons obtained from the LP optimal solution. As it explained in DRTS model overcomes the extreme result of the LP model and presents a smooth dispatching plan for haulage system.

Table 4.27 exhibits the waiting time at shovels and crusher observed when using the SRTS model for 100 replications in Arena simulation software. According to the table the average waiting time for 100 replications at crusher is 21 minutes and for shovel #4 is 6 minutes. Because of the blending requirement in the LP model, about 50 percent of the final number of trips for truck type ***B*** is related to the number of trucks which has been sent to the mining area #4. This issue also can be seen in the simulation models.

Table 4.27: Waiting time at servers in the SRTS model

Waiting time (seconds)					
Description	average	Half width	Minimum average	Maximum average	Maximum value
Crusher	1303	17.5	1081	1535	3809
Shovel #1	25.7	2	6.2	56.2	610
Shovel #2	119	6	53.5	252.7	1366.8
Shovel #3	0.8	0.4	0	10.8	237.9
Shovel #4	313.7	5.4	243.4	375	1150.9
Shovel #5	141.5	5.5	81.6	225.7	1111

Table 4.28 shows the shovels and crusher utilization for 100 replications in Arena simulation software. According to the utilization of servers in SRTS model, crusher is used 100 percent of the time and shovel #4 is used for about 90 percent of the time during the shift.

Table 4.28: Utilization of servers in SRTS model

Utilization of servers (percent)			
Description	average	Minimum average	Maximum average
Crusher	1	1	1
Shovel #1	0.39	0.3	0.4
Shovel #2	0.5	0.4	0.6
Shovel #3	0.1	0.1	0.2
Shovel #4	0.9	0.88	0.97
Shovel #5	0.5	0.4	0.6

In previous section results of the stochastic simulation models was compared with results of the deterministic simulation models and LP model.

In Section 4.3, crusher was the bottleneck which was working about 100 percent during the simulation runs. In the next section, other states that can be reflected as bottlenecks in the operational system will be tested in order to verify the proposed simulation model and validate the LP solution.

4.4 Different scenarios

In order to evaluate the new dispatching system, the main operational components such as number of trucks and shovel loading time will be considered as bottleneck of the haulage system. The reason can be seen in importance of new model behavior in different situations in comparison by the LP model.

In the next section the number of trucks is considered as bottleneck of the operational system.

4.4.1 Trucks as a bottleneck

In this section, we first present the results of the LP model considering the number of trucks as variable in the model in order to create a scenario where truck capacity will be the bottleneck of the system. The objective of this part is to determine the situation of our case study in terms of the number of trucks to see if the system is under truck (there is not enough trucks) or over truck (there are additional trucks in the mine). We must change the LP model in order to determine the minimum number of required trucks for each type. This new model considers the number of trucks of each type as an integer variable. Moreover, we add constraints in order to produce the same amount of the ore production during the shift as the one obtained from the previous LP model. The new objective function consists in minimizing the number of trucks ***A*** & ***B*** used. The following changes have been implemented in LP model.

- Consider the number of truck ***A*** & ***B*** as variables in the model

NTA	Number of truck A
NTB	Number of truck B

- Change the objective function for:

$$Minimize\ z = \sum_{i \in I} \sum_{j \in J} NTA + NTB \tag{4.1}$$

- Add the following constraints to the LP model

$$\sum_{i \in I} \sum_{j \in J_c} \sum_{k \in K} CA_k .X_{ijk} \geq 73100 \tag{4.2}$$

$$NTA \in \mathbb{N} \quad \text{and} \quad NTA \geq 0 \tag{4.3}$$

$$NTB \in \mathbb{N} \quad \text{and} \quad NTB \geq 0 \tag{4.4}$$

Constraints 4.2 presents the minimum amount of the ore production according to the result of the SRTS model because, results from the SRTS model are more reliable and accurate. Constraints (4.3) and (4.4) guarantee the integrality and non-negativity of the number of trucks in the model.

According to the above changes the following result presents the tonnage of the extracted material and also the optimal number of essential trucks in order to transport the mentioned extracted material. Table 4.29 shows the result of the modified LP model.

Table 4.29: Tonnage of extracted ore and waste in modified LP model

Amount of extracted material (ton)	LP Optimal result
Ore	73250
Waste	18350

The number of tons of ore remains the same, but the number of tons of waste is reduced to 18350 tons which corresponds to the minimal amount of waste necessary to respect the stripping ratio.

Table 4.30 shows the minimum number of required trucks in this case study.

Table 4.30: Number of required trucks

Type of the truck	Number of each truck
Truck type ***A***	1
Truck type ***B***	13

Comparing the results of the LP model and SBS model – truck as a bottleneck

In this section the SBS model has run using the 1 truck type ***A*** and 13 trucks type ***B***. Table 4.31 presents the result of the SBS model and LP model solution. This table emphasizes the fact that the LP model is too optimistic and produces large amount of ore in comparison with the SBS model using the same number of trucks during the simulation. The reason is that the LP model does not consider waiting time at service points such as shovels and crusher and assumes trucks are working continuously during the shift. While SBS model takes into account the waiting time at service points. In this model, when a truck waits to be served by crusher or shovel during the simulation, system losses time and then produces small amount of ore in comparison with the LP solution.

Table 4.31: Result of the LP and SBS models-truck as a bottleneck

Quantity of extracted material (ton)	LP model result	SBS model*
Ore	73250	64227.5
Waste	18350	16355.5

* Average amount of 100 replications

Table 4.32 shows the waiting time at shovels and crusher in SBS model-trucks as bottleneck for 100 replications in Arena simulation software. According to the table, the average waiting time for 100 replications at crusher and shovel #4 is about 4 minutes. According to the LP optimal solution, the maximum numbers of trucks are sent to shovel #4 during the shift. Since, the SBS model is based on the result of the LP model and follows it as a target, then the result of the following tables show the longest waiting times in this shovel. In the LP model about 49 percent of the final number of trips for truck type ***B*** is related to the number of truck which has sent to the mining area #4. This issue also can be seen in the SBS model.

Table 4.32: Waiting time at servers in SBS model-truck as a bottleneck

Waiting time (seconds)					
Description	average	Half width	Minimum average	Maximum average	Maximum value
Crusher	217.7	4.3	172.5	281	2534
Shovel #1	11.1	1.26	0.37	33.5	569.3
Shovel #2	53.2	3	27.2	93.5	864.6
Shovel #3	0	0	0	0	0
Shovel #4	207.8	7.6	125.5	313.9	1212
Shovel #5	37.7	1.9	19.7	63.7	628

Table 4.33 indicates the utilization of the servers in SBS model when truck is considered as bottleneck. As it can be seen from the following table the utilization of crusher is reduced from 99 percent to 87 percent during the shift. The reason is reduction in the number of trucks in the system which will decrease the number of trips between crusher and mining areas.

Table 4.33: Utilization of the servers in SBS model-truck as bottleneck

Utilization of servers (percent)			
Description	average	Minimum average	Maximum average
Crusher	0.87	0.83	0.92
Shovel #1	0.34	0.3	0.38
Shovel #2	0.4	0.38	0.49
Shovel #3	0.12	0.09	0.14
Shovel #4	0.86	0.81	0.91
Shovel #5	0.5	0.4	0.5

In the next section, the result of the SRTS model while considering trucks as bottleneck of system will be presented.

Comparing the results of the LP model and SRTS model – truck as a bottleneck

Table 4.34 shows the result of the SRTS model when the truck is considered as bottleneck. Also, this result is compared with the result from the LP model. This table emphasizes the fact that the LP model is too optimistic. This model has a better result than the SBS model. The reason is considering the constraint in this model which penalize the direction that will have waiting time at shovel.

Table 4.34: Result of the LP and SRTS models-truck as a bottleneck

Quantity of extracted material (ton)	LP model result	SRTS model*
Ore	73250	66833.5
Waste	18350	17087.5

* Average amount of 100 replications

Table 4.35 contains the data for the waiting time at shovels and crusher in SRTS model when trucks are considered as bottleneck for 100 replications in Arena simulation software. According to the table, the average waiting time for 100 replications at crusher is 4.6 minutes and for shovel #4 is about 5.3 minutes. In this table, the average waiting time by less number of trucks is decreased by 79 percent in comparison with the result of the SRTS model with 8 trucks type ***A*** and 16 trucks type ***B.***

Table 4.35: Waiting time at servers in SRTS model-truck as a bottleneck

Waiting time (seconds)					
Description	average	Half width	Minimum average	Maximum average	Maximum value
Crusher	274.5	5.7	201.2	335.3	2264.8
Shovel #1	19.4	2	1.6	44.5	565.6
Shovel #2	69.9	4.4	21.6	141.4	967.4
Shovel #3	0.87	0.6	0	20	380.7
Shovel #4	320	5.5	252.7	389.4	1249.3
Shovel #5	141.3	5.3	92	207.4	1125.4

In the SRTS model, according to the following table, utilization of the crusher is about 91 percent of the time and also this percentage for shovel #4 is equal to 93 percent during the shift. Table 4.36 presents the utilization of servers in SRTS model when truck is considered as bottleneck of the operational system.

Table 4.36: Utilization of servers in SRTS model-truck as bottleneck

Utilization of servers (percent)			
Description	average	Minimum average	Maximum average
Crusher	0.91	0.87	0.94
Shovel #1	0.35	0.3	0.4
Shovel #2	0.42	0.33	0.5
Shovel #3	0.13	0.09	0.2
Shovel #4	0.93	0.85	0.98
Shovel #5	0.47	0.41	0.53

Considering the number of trucks as bottleneck indicates the LP optimal solution is too optimistic. All the result shows using the optimal number of trucks in the mine will result in less production in SBS and SRTS models. In the next section the result of the LP model, SBS and SRTS model will be presented when the shovels are the bottleneck of the operational system.

4.4.2 Shovels as a bottleneck

In this section, we will change shovels' loading time in the LP model in order to create a system where the server in mining area will be considered as the bottleneck. Table 4.37 shows the result of the LP model when the shovel loading time is increased from 250 to 540 seconds for truck type ***A*** and from 300 to 600 seconds for truck type ***B*** during the shift. However these shovel loading times are unrealistic but, it was the easiest way to create a system where servers are the bottleneck. As it can be seen from the table, the amount of the ore production reduced for about 35 percent and about 60 percent for waste production.

Table 4.37: Tonnage of extracted ore and waste in LP model-shovel as a bottleneck

Amount of extracted material (ton)	LP Optimal result
Ore	49750
Waste	12600

The following section presents the result of the LP model and SBS model when the loading time at shovels is considered as the bottleneck of the system.

Comparing the results of the LP model and SBS model – shovel as a bottleneck

In this section, the SBS model has been run using the increased loading time at shovels. Table 4.38 shows results for the SBS model and compares these results with those obtained by LP model when the shovel is considered as bottleneck of the operational system. As it can be seen from the table, the result of the SBS model is less than the LP model but the difference is too small and is negligible.

Table 4.38: the result of the LP and SBS models- shovel as a bottleneck

Quantity of extracted material (ton)	LP model result	SBS model*
Ore	49750	49567.5
Waste	12600	12600

* Average amount of 100 replications

Table 4.39 shows the waiting time at shovels and crusher in SBS model when loading time at shovels are considered as bottleneck for 100 replications in Arena simulation software. According to the table, the longest average waiting time for 100 replications is at shovel #2 and after that at shovel #4 and shovel #5 which is between 28 to 34 minutes. In the result of the LP model, the number of trips for these three areas is the maximum trips of the truck during the shift.

Table 4.39: the waiting time at servers in SBS model-shovel as a bottleneck

Waiting time (seconds)					
Description	average	Half width	Minimum average	Maximum average	Maximum value
Crusher	273.3	6.9	204.1	374.2	3851
Shovel #1	94.9	8.5	28.5	220.2	1435
Shovel #2	2040.4	142	577	3784.5	5843
Shovel #3	5.6	2	0	49.4	685
Shovel #4	1893	145.9	504.7	3680.6	5791
Shovel #5	1663	38.4	1190.4	2187.5	3992.8

The table 4.40 presents the utilization of the servers in SBS model when shovel is considered as bottleneck. As it can be seen in the following table the utilization of shovel #2 and shovel #4 is equal and is 95 percent and this value for shovel #5 is 79 percent during the shift. When the crusher was the bottleneck, the utilization of shovel #2 and shovel #4 was 51% and 92%

respectively. The shovel #5 utilization was 96%. In case of having trucks as bottleneck, the utilization of shovel#2 and shovel #4 was 0.4% and 0.86% respectively. The utilization of shovel #5 was 0.5%. Increasing the shovel loading time makes more shovel utilization in comparison with the other scenarios when crusher and trucks were the bottleneck. But as production of waste is reduced the utilization of shovel#5 is decreased from 96% in case of crusher as bottleneck to 79% in the latest case.

Table 4.40: the utilization of servers in SBS model-shovel as bottleneck

Utilization of servers (percent)			
Description	average	Minimum average	Maximum average
Crusher	0.71	0.63	0.78
Shovel #1	0.56	0.46	0.63
Shovel #2	0.95	0.92	0.97
Shovel #3	0.23	0.17	0.29
Shovel #4	0.95	0.81	0.97
Shovel #5	0.79	0.66	0.89

The next section presents the result of the SRTS model when the loading time at shovels is considered as bottleneck.

Comparing the results of the LP model and SRTS model – shovel as a bottleneck

The result of the SRTS model is shown in Table 4.41. This table compares this result with the LP model when the shovel is considered as bottleneck of the operational system. As it can be seen in the table, the result of the SRTS model is less than the LP model. According to the Table 4.40 the quantity of waste in SRTS model is more than LP model but the total extracted material in SRTS model is less than the LP model. In this scenario, the LP model tries to maximize the amount of ore during the shift. So, we can have infinite number of solutions which have the equivalent objective function in terms of amount of ore but with different distribution of trucks. Also, the amount of waste production in this case would be changed from one solution to another one.

Table 4.41: Result of the LP and SRTS models- shovel as a bottleneck

Quantity of extracted material (ton)	LP model result	SRTS model*
Ore	49750	42816.5

Quantity of extracted material (ton)	LP model result	SRTS model*
Waste	12600	18434.5
Total	62350	61251

* Average amount of 100 replications

Table 4.42 presents the waiting time at shovels and crusher in SRTS model when loading time at shovels is considered as bottleneck for 100 replications in Arena simulation software. According to the table the average waiting time for 100 replications at shovel #5 is about 68 minutes which is the longest waiting time among other shovels. Afterwards, the waiting time at shovel #2 and shovel #4 are the longest waiting time during the shift. Since the loading time at shovels is increased then the waiting time at shovels will be increased that has shown in the output of the simulation model.

Table 4.42: Waiting time at servers in SRTS model-shovel as a bottleneck

Waiting time (seconds)					
Description	average	Half width	Minimum average	Maximum average	Maximum value
Crusher	257.4	4.3	190.5	349.4	3645.1
Shovel #1	84.7	6.7	20.6	212	1459.9
Shovel #2	2272.2	37.8	1717	2752.8	5257.6
Shovel #3	8.4	3.1	0	83.8	777.8
Shovel #4	1516.8	22.7	1277.1	1867.1	3517
Shovel #5	4095.9	87.2	3203.5	5363.3	14804

Table 4.43 displays the utilization of the servers in SRTS model when shovel is considered as bottleneck. As it can be seen in the following table the utilization of shovel #5 is 99 percent and shovel #4 is 93% and this value for shovel #2 is 76% during the shift. According to Table 4.28 when the crusher was the bottleneck, shovel #5 utilization was 50%. Utilization of shovel #4 and shovel #2 were 90% and 50% respectively. When the truck was the bottleneck utilization of shovel #5 was 47%. Utilization of shovel #4 and shovel #2 were 93% and 42% respectively.

These results verifies the effect of the increased shovel loading time in the utilization of the shovels which is increased as following tables especially for the shovels which have sent more trucks during the shift .

Table 4.43: Utilization of servers in SRTS model-shovel as bottleneck

Utilization of servers (percent)			
Description	average	Minimum average	Maximum average
Crusher	0.61	0.51	0.67
Shovel #1	0.49	0.38	0.57
Shovel #2	0.76	0.6	0.85
Shovel #3	0.2	0.15	0.26
Shovel #4	0.93	0.72	0.94
Shovel #5	0.99	0.98	0.99

In the next section the summary and remarks of this chapter will be presented.

4.5 Summary and remarks

The LP model and the simulation models that were developed in Chapter 3 are applied on a real mine in this chapter. The DBS model result presents the operational dispatching plan for truck and shovel system in the mine.

According to the output of the simulation models, crusher was the bottleneck of the simulation models. So, at the end of this chapter the possibility of having the bottleneck in other parts of the operational system was tested. The result of the simulation models when trucks are considered as bottleneck indicates that the result of LP model is too optimistic.

In the next chapter the summary and conclusion of the thesis will be presented.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

This chapter contains conclusion of the thesis, as well as recommendations for future work in studying truck and shovel hauling systems in an open pit mine for a very short-term-term period.

5.1 Conclusions

The LP model was developed by Gamache et al. (2009) with the suitable level of detail, and many different aspects of truck and shovel operations has run using Solver. This model does not take into account the waiting time at servers.

After running the basic simulation model which considers the waiting time at shovels and crusher, and also the real time simulation model crusher discovered as a bottleneck of the operational system.

Considering truck as a bottleneck of the system presents that the LP model is too optimistic and not taking into account the waiting time will cause reduction in the ore production in the SBS model. The result of the SRTS model confirms the above fact and also produces more ore in comparison with the SBS model. The reason is using the constraint in this simulation model which penalizes the direction that will have the waiting time.

The shovel loading time is the other bottleneck of the system. In this situation also the LP model and simulation models have run for 12 hours shift. In this scenario, the SBS model has the same amount of waste production as LP model but less ore production that is negligible. In the SRTS model we have much less ore production but the more amount of waste production. The reason can be seen in the fact that the LP model tries to maximize the ore production. The LP model has different solutions with the same amount of ore but different solutions in terms of trucks distribution and waste production.

In the next section recommendation for future research will be presented.

5.2 Recommendations for future research

The following recommendations could improve the truck and shovel hauling system and researches in this area.

- Apply Opt Quest tool in Arena in order to maximize ore production according to the LP model constraints
- Scheduled and unexpected failures of trucks, shovels, and crushers and repairing processes could be added to the model to create a more precise valuation of the system.
- A time study with probability analysis to determine the cycle time more accurately.
- A sensitivity study of input parameter to understand how the system reacts to the different scenarios.

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