OPEN-PIT TRUCK/SHOVEL HAULAGE SYSTEM SIMULATION

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ABSTRACT

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This thesis is aimed at studying the open pit truck- shovel haulage systems using computer simulation approach. The main goal of the study is to enhance the analysis and comparison of heuristic truck dispatching policies currently available and search for an adaptive rule applicable to open pit mines. For this purpose, a stochastic truck dispatching and production simulation program is developed for a medium size open pit mine consisting of several production faces and a single dump site using GPSS/H software. Eight basic rules are modeled in separate program files. The program considers all components of truck cycle and normal distribution is used to model all these variables. The program asks the user to enter the number of trucks initially assigned to each shovel site.

Full-factorial simulation experiments are made to investigate the effects of several factors including the dispatching rules, the number of trucks operating, the number of shovels operating, the variability in truck loading, hauling and return times, the distance between shovels and dump site, and availability of shovel and truck resources. The breakdown of shovel and trucks are modeled using exponential distribution. Three performance measures are selected as truck production, overall shovel utilization and overall truck utilizations. Statistical analysis of the simulation experiments is done using ANOVA method with Minitab software. Regression analysis gives coefficient of determination values, R^2, of 56.7 %, 84.1 %, and 79.6 % for the three performance measures, respectively. Also, Tukey's method of mean comparison test is carried out to compare the basic dispatching rules. From the results of statistical analysis, it is concluded that the effects of basic truck dispatching rules on the system performance are not significant. But, the main factors affecting the performances are the number of trucks, the number of shovels, the distance between the shovels and dump site, finally the availability of shovel and truck resources. Also, there are significant interaction effects between these main factors. Finally, an adaptive rule using the standardized utilization of shovels and trucks is developed.

Keywords: Open Pit Truck-Shovel Haulage systems, Truck Dispatching, Heuristic Rules, Discrete-Event System Simulation Approach, and GPSS/H Software.

ÖZ

AÇIK OCAK KAMYON/EKSKAVATÖR TAŞIMA SİSTEMLERİN SİMÜLASYONU

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Bu çalışma, bilgisayar simülasyonu yöntemi kullanılarak açık ocak kamyon – Ekskavatör sisteminin araştırılmasını amaçlamaktadır.Çalışmanın temel amacı, mevcut olan hüristik kamyon atama kurallarının analizi ve karşılaştırılmalarını incelemektir.Bu amaçla, birkaç üretim panosu ve bir tek döküm sahasından oluşan orta ölçekli bir maden için GPSS/H simulasyon paket programı kullanılarak olasılıklı bir kamyon atama ve üretim modeli geliştirilmiştir. Sekiz değişik hüristik kural, ayrı ayrı programlar olarak kodlanmıştır. Program kamyon devir sürelerinin bileşenlerinin tamamını içermektedir. Normal dağılım fonksiyonu bütün devir bileşenlerinin modellemesinde kullanılmıştır. Program kullanıcıya, her bir ekskavatöre başlangıçta yapılan kamyon sayılarını sormaktadır.

Tam faktörlü simülasyon deneyleri sekiz ayrı faktörün araştırılması için yapılmıştır. Bu faktörler, kamyon atama kuralı, kullanılan kamyon sayısı, kullanılan ekskavatör sayısı, kamyon yükleme, taşıma ve geri dönüş sürelerindeki değişim, ekskavatör ile döküm sahası arasındakı mesafe, ve kamyon ve ekskavatörlerin kullanım randımanlarıdır. Kamyon ve ekskavatörlerin arızaları üstel dağılım fonksiyonu kullanılarak modellenmiştir. Performans ölçütleri olarak ta, kamyon üretim miktarı, toplam ekskavatör kullanma oranı ve toplam kamyon kullanma oranları alınmıştır.Simülasyon deneyleri sonuçları, ANOVA metodu ile Minitab paket programı kullanılarak istatistiksel olarak analiz edilmiştir. Regrasyon analizleri sonucunda bu üç performans ölçüsü için R^2- degerleri sirasıyla, 56.7 %, 84.1 % ve 79.6 % olarak hesaplanmıştır. Tukey testi ile de bu temel kamyon atama kuralları istatistıksel olarak karşılaştırılmıştır. Yapılan analizler sonucunda, temel kamyon atama kurallarının performans ölçütlerini fazla etkilemedikleri sonucuna varılmıştır. Fakat, performasları etkileyen ana faktörlerin, kullanılan kamyon sayısı, kullanılan ekskavatör sayısı, döküm sahasına olan mesafe ve ekipmanların kullanma randımanlarını olduğu sonucuna varılmıştır. Ayrıca, bu etkileyen temel faktörler arasında da oldukça ikili etkileşmenin olduğu gözlemlenmiştir. Son olarak, kamyon ve ekskavatörlerin standartlaştırılmış kullanma oranları kullanılarak yeni bir adaptif kamyon atama kuralı geliştirilmiştir.

Anahtar Kelimeler: Açık Ocak Kamyon- Ekskavatör Sistemi, Kamyon Atama, Hüristik Kurallar, Kesik-Olaylı Sistem Simülasyon Metodu, GPSS/H Simülasyon Programı

To My Parents and My Dear Grand Mother Dudu ELMAS

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SYMBOLS

GPSS	General Purpose Simulation System
ANOVA	Analysis of Variance
TP	Total Production
SU	Shovel Utilization
TU	Truck Utilization
DR	Dispatching Rule
NT	Number of Operating Trucks
S	Number of Operating Shovels
LT	Truck Loading Time
HT	Truck Hauling Time
RT	Truck Returning Time
SDD	Distance Between Shovels and Dumping Point
A	Shovel and Truck Availability
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
FTA	Fixed Truck Assignment
MSPR	Minimizing Shovel Production Requirement
MTWT	Minimizing Truck Waiting Time
MSWT	Minimizing Shovel Waiting Time
MTCT	Minimizing Truck Cycle Time

MSC	Minimizing Shovel Coverage
ELS	Earliest Loading Shovel
LWS	Longest Waiting Shovel
AR	Adaptive Rule
K	Shovel Number to Which Truck is Assigned
TNOW	Time Elapsed from Start of Shift
TSHIFT	Total Shift Time
P_i	Actual Shovel Production at Current Time
PO_i	Shovel Target Production
SR_i	Ready Time of Shovel for Loading This Truck
TR_i	Ready Time for The Truck to Be Loaded by The Shovel
TCT	Truck Cycle Time
TT	Mean Truck Travel Time from Dispatching Point to Shovel
STU	Standardized Truck Utilization
TU_{cur}	Current Truck Utilization
TU_{mean}	Mean Truck Utilization
SDTU	Standard Deviation of Truck Utilization
SSU	Standardized Shovel Utilization
SU_{cur}	Current Shovel Utilization
SU_{mean}	Mean Shovel Utilization
SDSU	Standard Deviation of Shovel Utilization

CHAPTER 1

INTRODUCTION

Surface mining involves the basic procedures of topsoil removal, drilling and blasting, ore and waste loading, hauling and dumping and various other auxiliary operations. Loading of ore and waste is carried out simultaneously at several different locations in the pit and often in several different pits. Shovels and frond-end loaders of various sizes are used to load material onto trucks. Hauling material from the shovel production faces to the dumping sites must be accomplished through a network of haul roads of various length and grades. Haul roads can be extremely complex, cover large surface areas and pass through extreme elevation changes. Loading times of shovels depends on shovel capacity, digging conditions, and the truck capacity. Queues often will form at the shovels since trucks of various sizes may be used at individual shovels. Thus, allocation of trucks to haul specific material from a specific pit or shovel becomes a complex problem. Obviously, efficient mining operations are strongly dependent on proper allocation of trucks to shovels and the respective allocation of trucks along the appropriate haul roads and dump sites. The number and type of trucks and shovels are two important factors in determining the optimum design parameters of an open-pit mining system. Also, the characteristics of truck's arrival and loading times at shovels determine the performance measures (i.e. total production) of truck-shovel system. The assumptions of identical truck travel and loading times may result in underestimating or overestimating the performance of these systems.

The ability to assess the performance of a truck-shovel system in open-pit mines accurately would be a very useful device for mining companies. Any marginal improvement in the performance would save a significant amount of money in most modern open-pit mining operations where very large capital investments are required to purchase and replace the necessary equipment. Accurate assessment of the system performance is not so easy because of the complexity of the system. However, with some simplifying assumptions one can obtain fairly accurate results using computer simulation techniques for all practical purposes.

One of the major issues in open-pit mining operations is the selection of trucks and shovels that would satisfy some economic and technical criteria optimally. This problem is faced at the design stage of the mine as well as during the operation of the mine where there may be a need to redesign for expansion purposes. The solution lies in efficient prediction of performance parameters for various combinations of trucks and shovels under realistic assumptions. These parameters could be used to determine the impact of different scenarios on the productivity of the operation and select the best promising alternative for actual design goals. Given the characteristics of the truck-fleet, dynamic routing of trucks to different service areas (i.e. loading and dumping) cannot be done arbitrarily since this would seriously affect the productivity of the mine. Therefore, it is very important for optimal operation that the design parameters should be determined accurately and applied at all stages of mining operation.

Efficient truck dispatching represents a traditional approach to improve production equipment utilization in open-pit mining operations. Increasing the equipment utilization can result in a greater increase in the profitability of operation and decrease in the truck-fleet size as well as increase in production. Truck haulage represents 50% or more of the total operating costs in most surface mines (Kennedy, 1990), and efforts have been made to reduce these high haulage costs. These include improving operating performance of the trucks resulting in higher efficiency and reliability, increasing the payload capacity of trucks, employing in-pit crushers and conveying systems with truck haulage, and using trolley-assisted trucks to reduce the truck cycle times. Another concept currently under development is the use of driver-less trucks since this approach has the potential to reduce the labor costs. These effort have focused on truck or haulage system designs. The same cost reduction goals can also be realized by more efficient utilization of trucks and shovel resources, which is primary objective of computer-based truck dispatching systems. With computer-based truck dispatching, one hopes either to increase production with existing truck and shovel resources or meet the desired production goals with reduced equipment requirements. This goal is achieved with careful consideration of assignment decisions that increase utilization of truck and shovel resources and reduce waiting times in the haulage network. Haulers are only productive when they are carrying a load and loaders are also only productive when loading material for haulage. Idle equipment times are the essence of non-productive equipment and they have to be minimized.

Truck dispatching issue is one of assigning trucks to shovels in a well-designed system on real-time basis so as to ensure the achievements of some goals or minimize the underachievement of such goals. The general problem solved by truck dispatching routines is to determine the shovel to which the current truck at the dispatching station should be assigned. The objective of computer-based truck dispatching is to improve the equipment utilization and increasing production subject to a variety of practical constrains. A computer truck dispatching system consists of two main components as hardware and software. Developments in hardware are concentrated on signal acquisition and transmission equipment and computer. Computational procedures are becoming relatively easier with the development of high-speed computers. Also, truck dispatching software presents many opportunities for improving the performance of open-pit mining systems.

Truck-shovel system is a complex mining system with respect to its stochastic features and interaction between system elements. It is naturally impossible to derive some global optimal solution algorithm for truck dispatching problem (Tan an Ramani, 1992). Therefore, every dispatching criterion is based on a consideration of local optimization. Various methods have been employed to model truck-shovel system. Some of these methods rely on empirical rules or trial and error and some are highly mathematical requiring significant computational effort. Analysis of open-pit truck-shovel system using computer simulation is a well-established procedure since it allows incorporating the inherent variability and complexity of the system.

This thesis is divided into six chapters including the introduction. A through literature review of truck dispatching systems and simulation models and the purpose of the thesis are presented in Chapter 2. The eight basic heuristic truck dispatching policies programmed together with the new adaptive rule are discussed in Chapter 3. Chapter 4 presents the input data sets and the basic assumptions made, and explains in detail the development and the general structure of the simulation model. The design of simulation experiments together with the statistical analysis performed over the results and discussions are presented in Chapter 5. Finally, the conclusions and the recommendations for further research made are given in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Problem Statement

The purpose of this research is to develop a stochastic truck dispatching and production simulation model program for a medium-sized open pit mine consisting of several production faces and a single dump location. We have used GPSS/H software to investigate the effects of several basic heuristic truck dispatching criteria currently available. The main objective of this research is to enhance the analysis and comparison of heuristic truck dispatching policies and search for a hybrid rule applicable to open pit mines.

Another aspect of this research is to develop animation of a truck dispatching system to aid users to observe dynamic activities in a truck-shovel system and follow the logic and assumptions of a simulation model readily. The specific objectives are to:

1. study the impact of various heuristic dispatching policies;
2. test and compare several heuristic dispatching strategies for improving haulage productivity;
3. serve as a planning tool for estimating the expected production of a given truck haulage system;
4. reveal bottlenecks in a proposed truck haulage system;

5. use animation as a tool to convince decision-makers and to train dispatchers.

2.2 Truck dispatching systems

The significant improvements in computer technology have led the mining industry to develop several decision making models for deciding the best possible assignment of trucks in an open-pit mine. Computerized truck dispatching systems were developed in the late 1970`s and have become the common mode of operation at many large open pit mines. But, they were not economically justified for small and medium-sized haulage operations due to high costs of implementation. Fortunately, tremendous improvements in computer hardware and decreases in costs occurred since late 1980`s as well as the need for to increase productivity and equipment utilization. Truck dispatching systems can be classified into three major categories as: manual, semi-automated and full automated. Most of the dispatching systems in the literature are either semi-automated or full automated. The benefits and shortcomings of the dispatching systems are outlined in the following sections.

2.2.1 Manual Dispatching systems

The manual dispatching system is the standard practice of truck assignment. The trucks are assigned to a particular shovel and dump point at the beginning of the shift, changing the circuit according to the dispatcher's best judgment of the situation based on production requirements, shovel locations, fleet availability, etc. In this system, the decision making requires a dispatcher located at a strategic point in the pit to oversee the operation and kept tract of the equipment status and location. The effectiveness of the system relies heavily on the use of radio-transmitted information and therefore both shovels and trucks are equipped with two-way radio to allow communication. The system has been used in open-pit mining operations since the early 1960`s and it is recommended for small mines having, say up to 10 operating trucks.

Mueller (1977) described a manual system based on a dispatch board which can be used as an analog computer. The objective of the board is to aid the dispatcher in keeping track of the status and position of the equipment in the pit and guide his decision making process. The main components of the board are trucks and shovels represented by blocks. The decision for dispatching is taken after the truck has dumped its load at which point the operator communicate with the dispatcher. The dispatcher then adjusts the board to correlate with the equipment in the pit in order to make the proper assignment. The dispatcher has to rely on his personal judgment and professional experience in a particular pit.

2.2.2 Semi-Automated Dispatching Systems

In a semi-automated system, the computer is programmed to aid the dispatcher in the decision making process for assigning the trucks. A digital computer is used to record the status of equipment and the location of trucks which make up the haulage fleet. The computer is also used to assist the dispatcher to assign the trucks to shovels according to the dispatching strategy applied. The system is called semi-automated since the computer does not have direct contact with the equipment and the dispatcher is necessary to communicate all instructions. The dispatcher correlates this information with the actual position of equipment in the pit and takes an independent decision which may or may not agree with the computer suggested assignment. The dispatcher relays information manually by radio or visually.

The main advantage of this dispatching system is that it facilitates recording of events, generating production reports and reduction of equipment waiting times. Using this system, the maximum achievable production will be a function of the dispatching policy applied. Therefore, the models developed for semi-automated systems must be as flexible as possible to allow changes in operating policies according to the prevailing conditions at any particular time. This system is applicable to medium-sized mines, say up to 20 operating trucks.

Hodson and Barker (1985) described the implementation of semi-automated dispatching system and the upgrading of a passive system which only records information to the one where computer suggests the optimal truck assignment. The assignments are based on a two step process. In the first step, each shovel is guaranteed a certain number of trucks. In the second step, the distribution of the trucks within a sub-system represented by dumps is regulated according to the shovel loading time. The dispatcher has complete control of the operation. Dispatching is done on the basis of determining an optimum cost per ton/match factor relationship for various cycle times. As soon as the truck driver requests an assignment, the computer calculates the match factor of a particular shovel in that dump's sub-system. When this is within a pre-specified optimum range, the trucks remain in that sub-system, and the truck is subsequently dispatched by the computer to the best available shovel. If the chosen sub-system has more trucks than required, the computer tests other sub-systems and reassigns the truck to the sub-system which has less than the required number of trucks. To control the distribution of trucks in each sub-system, the second step is used. This is done because the trucks are dispatched based on an average system match factor. In this strategy, the trucks do not change routes very often since at the beginning of shift, the dispatcher matches the trucks and shovels.

2.2.3 Automated Dispatching Systems

The fundamental problem with both manual and semi-automated dispatching systems is the limited ability of human dispatcher to store and transfer large amount of information over a long time span in a very short processing time. This was the main reason for the development of full automatic dispatching systems and they are the most emphasized in current literature. Automated dispatching systems enable the computer to make the necessary decisions for dispatching trucks without any intervention by a human dispatcher. Truck locations are detected by sensors (i.e. signpost beacons) and sent to the computer, which calculate the destination for truck allocations using the chosen dispatching strategy applied as in semi-automated dispatching systems. The assignments are sent to trucks directly and appear on LCD displays mounted in truck's cabin or in a central location where trucks go by.

The advantage of such systems is that the dispatcher does no longer need to communicate instructions to the trucks or to keep track of the truck status. Automated dispatching systems have been reported (Lizotte and Bonates, 1987) to decrease truck haulage requirements from 5 to 35 percent. The benefits vary depending on type of material handling fleet, haulage network configuration and specific dispatching procedures. They provide precise and timely production reports and increase efficiency of the haulage equipments. The only drawback with this system is the high installation cost involved due to monitoring and transmission equipments required.

Himebaugh (1980) described an automated dispatching system called "DISPATCH", developed and marketed by Modular Mining Systems Inc., which aims to maximize productivity with available equipment or achieve a desired production with minimum equipment. Dispatching trucks to meet either of these objectives is a dynamic operation which requires continuous monitoring of route selection and shovel and truck status and location to determine optimal truck assignments. DISPATCH is the best known and most documented large-scale, computer-based, mine management system which controls truck-shovel operations at an open-pit mine. This is one of the most successful and powerful systems and is in use at many open-pit mines worldwide. The system was developed based on a real-time computer program and consists of two separate functions which allow communication between each other through a common data base. The system software is modular in design. In the first part, real-time operations are handled. The dispatcher's log is maintained in the second part of the program. This model can be used for both assisted and direct computer dispatch. The system accounts for shovel moves, shovel breakdowns, shovel digging changes, dump and crusher downtime, and changes in material types. The dispatcher basically manages the whole operation by simple monitoring of assignments supplied by the computer. The truck driver requests an assignment at the beginning of the shift and the system indicates when the truck arrives at the shovel and when it is loaded. The shovel operators provide information on the type of material being loaded, delay or breakdowns. DISPATCH assigns trucks to minimize queuing of trucks at shovels and to minimize shovel idle times using dynamic programming assignment logic. Current truck locations, speed factors and status, shovel digging rates, locations and status are all considered when determining truck assignments. DISPATCH tracks the location of trucks using data gathered from location beacons or from information entered into field control units by truck drivers. The productivity improvements of 10-15 % have been reported at mines using DISPATCH program (White et al., 1991).

2.3 Truck Dispatching Simulation Models

Simulation is the most commonly used technique for testing the dispatching algorithms. Besides queuing theory, which can be applied for very simple cases, simulation is the only practical method. Computer simulation can be used to obtain a feel with regard to the likely effect on mine environment. More detailed studies must be carried out to assess the feasibility of introducing a dispatching system and whether the benefits of increased efficiency would offset its installation and operating costs. A number of computer models have been developed to simulate truck dispatching systems. This section provides a review of simulation models developed to assess different heuristic dispatching strategies.

In a study by Cross and Williamson (1969), the effect of dispatching on fleet requirements was analyzed. The advantages of increasing the size of shovel were also studied. They compared a truck haulage system in the dispatching mode and non-dispatching mode. In the dispatching mode, trucks are assigned to the shovel which has been idle longest or would be idle next. In all studied cases, the dispatched system with one less truck hauled same tonnage as the non-dispatched system. The results of simulation have shown that the rate of production increase tended to decrease as the number of trucks operating increased. The study also pointed out that dispatching truck in open-pit mines tends to increase production by taking advantage of the irregularities within the system. There is more control over the operations and that reduces the disorder and improves the efficiency of the system. It was concluded that by using dispatching it is possible to reduce the number of operating trucks required for a specific production level, and the operating cost of the haulage is the most critical factor in any decision on the size and number of equipment of a particular operation.

Brake and Chatterjee (1979) developed an interactive stochastic simulation model consisting of two interconnected modules. They used the SIMULA modeling package and compared three different dispatching policies namely, fixed allocation, minimizing queuing at dumps and minimizing overall queuing. In the mine planning module, the cycle time elements for truck/shovel operation were calculated and the module allowed only lognormal distribution for all stochastic events. The model made dispatching decisions after dumping operation and simulated equipment breakdowns. The model predicted production and utilization increases of around 3-4 % for both shovels and trucks. The relatively small improvements were due to the size of the equipment fleet. It was concluded that greater improvements in productivity ant utilization would be realized over longer haul distances than over shorter distances. The other module, mine evaluation module, was used to evaluate mines already in production and required actual observed times for all load, haul and dump events.

The simulation model described by Kim and Ibarra (1981) was designed to study the effect of dispatching on productivity over a conventional mode of dispatching, i.e. fixed. The model used the minimum shovel waiting time strategy as the decision making criterion to assign the trucks to shovels. For analysis purposes, the input data were obtained from a real system and then adjusted and validated by comparing the results with a non-dispatching strategy. The model considered the characteristics of the haulage network, speed limits, right of way rules, equipment performances and availabilities, etc. Each route has a common intersection and it is compulsory for all trucks to pass through this point. This common intersection is used as the dispatch point where actual truck assignments are made. The results of this study indicated that dispatching increases truck/shovel productivity nearly 10 %, and also leads to a reduction of more than 30 % in truck and shovel idle times. A further conclusion was that dispatching yields greater improvements for combination of short and long haul roads.

The model described by Wilke and Heck (1982) was developed to study the existing methods of dispatching policies taking into consideration the equipment performance and the occurrence of equipment breakdowns during the shift. They recognized the importance of blending requirements as well as maximizing the fleet utilization. The model is based on a stochastic simulation and is divided into two parts. The first part of the model is used to simulate the equipment performance taking into account various truck speeds in different haul roads, different truck types, the haulage profile, and possible queuing at shovels and dumps. The second part is completely independent of the first part and is used to determine the probability of occurrence of breakdowns and their duration. The dispatching policy was to initially allocate trucks to shovels according to the production requirement and then assign empty trucks to shovels which are most behind their schedule, taking into account trucks which are already on their way.

Tu and Hucka (1985) developed a stochastic simulation model to analyze the performance of a truck/shovel operation considering various haulage networks and the effect of dispatching policies on productivity. The model is very flexible as it allows a choice of a number of different dispatching policies, namely fixed, maximizing shovel utilization and maximizing truck utilization. They used SLAM simulation language, which allows representing each truck and shoveling as an entity moving through a discrete event network. Shovels are also modeled as resources amenable to seizure when breakdowns and face moves occur. The model was validated by a comparison between the simulation results and actual production statistics. This study concluded that the use of dispatching systems in an open-pit mine can save at least one operating truck per shift, or 2-3 % of the total truck fleet. The study also showed that computerize dispatching is more effective when shovels are under trucked. When shovels are over trucked, the addition of a shovel results in a greater increase in production than that from computerized truck dispatching alone.

Billette and Seka (1986) developed a simulation model to assess the best assignment for the trucks and to determine the additional cost involved in blending operations. They claimed that the actual mining operation's efficiency is related to the financial efficiency. An attempt is made precisely to define the efficiency parameters involved. A production figure is obtained by simulating the operation on the basis of fixed assignment. These values were then compared with the values derived from analytical methods. The input data were obtained by using deterministic models to derive average values which were then fitted to weibull distribution. The parameters of this distribution were determined from past experience or from published literature. The results showed that for operation with small number of trucks, analytical method tended to underestimate the production compared to simulation model.

Lizotte and Bonates (1987) described a stochastic simulation program used to assess several dispatching rules applicable to small scale computerized systems for optimizing truck/shovel productivity. They tested the maximize shovel utilization, maximize truck utilization and shovel coverage strategies using their weibull-based simulation model to assess the potential improvements in productivity. The model does not consider any real particularities such as equipment breakdowns, scheduled breaks, shovel moves, etc. and single truck type was considered. The simulation program was structured on an advance clock approach which enabled the insertion of dispatching rules at various point in the haulage network and was written in FORTRAN.

Elbrond and Soumis (1987) presented an integrated production planning and truck dispatching procedure using mathematical optimization algorithms. For real-time dispatching, they proposed an assignment algorithm which minimizes the sum of squared deviation of the estimated truck waiting times from those of the operational plan for the current truck at dispatching point and the next 10-15 truck which will require assignment sooner. To test the dispatching strategy, they developed a simulation model. The model generates activity times according to Erlang distributions with mean and standard deviation corresponding to observed values. Simulation results predicted the gain in production of 3 % and reduction of 12 % in truck waiting times.

In the study carried out by Tan (1992), a simulation model using the SIMAN simulation language was developed to investigate a number of heuristic dispatching strategies on hypothetical mine data with varying number of trucks and distances between dispatch point and shovels. The study assumed a single dispatch point, identical trucks and identical shovels. Normal distribution was used for all event components. The results from the simulation runs showed that many dispatching criteria have good potential to increase the productivity but none of the basic heuristic dispatching rules can dominate all others. Some of the rules were performing better than other such as minimizing truck waiting time, minimizing truck saturation. He suggested searching for a hybrid dispatching strategy. He also suggested several modified heuristic strategies like Lizotte et al (1991).

Kolonja (1992) developed a SIMAN and CINEMA PC-based simulation model to simulate and animate truck-shovel operations of surface mines. The model is capable of simulating six dispatching strategies, which are minimize truck wait time (MTWT), minimize shovel wait time (MSWT), minimize shovel production requirement (MSPR), minimize truck cycle time (MTCT), minimize shovel saturation (MSC), and fixed truck assignment (FTA). He has also evaluated a mathematical dispatching strategy called DISPATCH using linear and dynamic programming. The model is an efficient planning tool for choosing optimal fleets. Based on the simulation results, it was concluded that DISPATCH and MTWT strategies show 4-5 % production improvement compared to fixed truck assignment. He also confirmed that rules based on minimum shovel wait times and minimum truck wait times are better suited for over trucked and under trucked systems, respectively. Finally, he concluded that there is no statistically significant difference in performance amongst all investigated heuristics, and this conclusion agrees with that of Tan and Ramani (1992).

Forsman and Vegenas (1992) developed a stochastic simulation model called METAFORA for determination and evaluation of dispatching strategies for operating loader/truck systems in mining. The model combines simulation and graphical animation with computer aided design. Two sizes of loaders and trucks can be used simultaneously. Three dispatching rules, (fixed, maximize loaders and maximize trucks) are modeled to simulate for evaluating alternative dispatch strategies. The simulation results indicated that maximize trucks rule performed better than others since truck waiting times at loading points are reduced.

Youdi et al. (1994) developed a stochastic simulation model using the event orientation approach in FORTRAN language for the haulage system of Yilan surface coal mine in China, consisting of eight shovels and three dumps. There were six heuristic truck dispatching alternative rules in the model. According to the different criteria, system simulation experiments were carried out under various mine conditions. The output of the simulation included the utilization of shovels and trucks, total coal and waste productions, and productions from each shovels. A comprehensive analysis and comparison of different dispatching criteria were made and the applicable ranges of each criterion under various operating number of trucks to shovel ratios were defined as a comprehensive dispatching criterion. Finally, a combined optimal dispatching criterion was

All components of the haulage system were represented by graphical modules. The model was run in both dispatching and non-dispatching modes with different fleet sizes in order to optimize the number of trucks in the system. Simulation results showed that the dispatching system is generally more productive than the non-dispatching mode. This improvement was significant in fleet sizes around the optimum. However, when the system is either under-trucked or over-trucked, the influence of the dispatching was not significant.

Kolonja et al. (2000) developed a stochastic simulation model for an open-pit transportation system to study the effect of a new in-pit crushing system on the productivity of a truck and shovel operation. The model is programmed in GPSS/H simulation language and animated with PROOF software to validate since it is designed for a new system. The model can be used to estimate production for various trucks and shovels configurations as a planning tool. The fixed truck assignment policy is applied as the operating dispatching strategy. The model determines the optimum number of trucks for various system configurations without considering mismatch. Economic analysis is done to evaluate two different transportation systems (i.e. truck haulage with and without in-pit crushing system). Simulation results showed that the truck haulage with in-pit crushing system is 50 % more costly than the truck haulage without in-pit crushing system.

2.4. A Critique of the Related Literature

In the above studies, simulation has been used to assess the effectiveness of various heuristic dispatching policies. A number of real-time dispatching systems are currently in operation at many mine sites all over the world using these various heuristic dispatching strategies. Most of the conclusions that are drawn from these simulation studies have already been proven to accurate and generally applicable. It has also been shown that the selection of the best dispatching strategy is a site-specific problem, especially where grade considerations and shovel production targets exist. However, generalizations can be made about the heuristic strategies which do not consider blending requirements. For example, the minimum truck waiting time strategy tends to favor shovels closer to dispatching point and the minimum shovel idle time strategy tends to balance out shovel utilizations more evenly across all the shovels while sacrificing the total production due to the longer travel times involved in reaching shovels located farther. A general conclusion which can be drawn is that dispatching can improve production in truck haulage systems by evenly distributing production and total waiting times between all equipment in use. The summary of truck dispatching simulation models is shown in Table 2.1. Basically, the modeling approach used depends on the model purposes, available data for study and simulation language used.

There are many basic heuristic truck dispatching policies applied to open-pit haulage operations. All the basic dispatching criteria can provide only a local optimum solution and heuristic rules are applied one-truck-at-a-time. The effects of basic dispatching criteria are varied greatly and each basic dispatch rule has its own suitable range for best performances. It is obvious that using a single dispatch criterion in a truck haulage system with dynamically changing conditions is not so realistic. The search for optimum dispatching criterion that will fit all conditions is not so realistic. However, based on the simulation results of a mine operation, several dispatching criteria which have good potential to increase performance can be selected. It is suggested that searching for the best combination of these basic criteria for a given mine situation is more desirable (Tan and Ramani, 1992). In this way, the advantage of multiple criteria can be taken according to the variation of haulage system conditions.

In above-mentioned studies, only Youdi et al. (1994) has considered the combined dispatching criteria for a typical surface coal mine and the system is always under the control of best dispatching criterion.

In this study, eight basic heuristic truck dispatching policies are modeled to simulate the truck and shovel operations in GPSS/H language. A combined truck dispatching criterion is developed using the standardized utilizations of trucks and shovels resources concurrently.

Table 2.1. Summary of Truck Dispatching Simulation Models

	Cross & Williamson (1969)	Brake & Chatterjee (1979)	Kim & Ibarra (1981)	Wilke & Heck (1982)	Tu & Hucka (1985)	Bonates & Lizotte (1986)	Tan (1992)
Software	N/A	SIMULA	GASP IV & FORTRAN	N/A	SLAM	FORTRAN	SIMAN
Animation	N	N	N	N	N	Graphical Display	N
Number of Dispatch Points	1	1	2	Multiple	Multiple	1	1
Number of Dispatch Rules	1	3	1	1	1	4	9
Equipment Breakdowns	N	Y	Y	Y	Y	N	N
Interactive	N	Y	N	N	N	N	N
Effect of Dispatching	Unit Operating Cost Decreased	Productivity Increased by 3.3 %	Productivity Increased by 10 %	Not Available	Saves One Operating Truck	Productivity Increased by 8 %	Productivity Improvement
Mine Size	Large	Large	Large	Medium	Large	Medium	Medium
Studied Policy	Heuristics	Heuristics	Heuristics	Heuristics	Heuristics	Heuristics	Heuristics

Table 2.1. Summary of Truck Dispatching Simulation Models (continued)

	Kolonja (1992)	Forsman & Vegenas (1992)	Youdi et al. (1994)	Temeng at al. (1997)	Baafi & Ataeepour (1999)	Kolonja at al. (2000)	Our Work (2004)
Software	SIMAN	Pascal	FORTRAN	SIMAN	Arena	GPSS/H	GPSS/H
Animation	CINEMA	Graphical Display	N	N	Arena	PROOF	PROOF
Number of Dispatch Points	1	1	1	1	1	Not Considered	1
Number of Dispatch Rules	8	3	6	1	1	Not Considered	9
Equipment Breakdowns	Y	Y	Y	Y	N	N	Y
Interactive	N	Y	N	N	Y	N	N
Effect of Dispatching	Productivity Increased by 4-5 %	Productivity Increased by 2 %	Productivity Improved	Productivity Increased by 15 %	Saves Three Operating Trucks	Not Considered	Productivity Improved Slightly
Mine Size	Medium	Large	Large	Large	Medium	Medium	Medium
Studied Policy	Heuristics & Math.	Heuristics	Heuristics	Math.	Heuristics	Not Considered	Heuristics

CHAPTER 3

TRUCK DISPATCHING HEURISTICS

3.1 Overview of Heuristics

Computerized truck dispatching systems require a procedure for assigning trucks to shovels in an open-pit truck/shovel haulage system. Each computerized system developed should employ a unique policy. In order to maximize fleet efficiencies, several methods ranging from simple heuristics to complex mathematical procedures can be applied in this decision-making process. The objective of any truck dispatching procedure is to increase the productivity of the system with the given fleet of trucks and shovels or a significant reduction in the number of trucks and shovels needed for a given production target subject to a variety of practical constraints. Reduction in truck and shovel waiting times contribute much to these goals. Dispatching policies consider different objectives in varying degrees of sophistication. For the heuristic rule-based dispatching systems, usually the dispatching decisions are taken when the truck reaches the dump site. They invoke a chosen heuristic rule; say minimizing truck waiting time, at the time of making a dispatching decision. The computer then checks the current status of the equipment in the mine and dispatches the trucks to the most appropriate shovel at that instant. The most appropriate shovel is determined as a function of the dispatching policy applied.

A heuristic procedure or algorithm can be defined as a relatively simple formula or procedure applied to solve a problem. In mathematical terms, heuristic algorithm in most cases can solve a problem, but cannot guarantee an optimal solution. In general, heuristic procedures consider only current objectives without consideration of future events or long-term planning goals. Often, the solutions of heuristic procedures are based on local (i.e. individual elements and short time) optimization. The dispatching algorithms based on heuristic rules are easier to implement and do not require much computation when making dispatching decisions in real-time. Typically, all heuristic rules are applied one-truck-at-a-time. That is, current truck assignment decision is made with indifference to the assignment of other trucks that will be made in the near future. Also, most heuristic rules ignore essential constraints or secondary goals of system operation such as maintaining product grade requirements by balancing production ratios among available loading sites.

In this study, the existing truck dispatching criteria currently available are reviewed and their definitions, primary considerations and basic characteristics are presented. The basic rules can be grouped into three categories as : criteria originated from consideration of optimizing equipment idle time measurements, criteria originated from maximizing truck productivity, and criteria originated from the optimization of the shovel production requirements. In the following sections, the basic rules that are modeled in this study are explained.

3.2 Fixed Truck Assignment (FTA)

In this strategy, each truck is assigned to a particular shovel and dump point at the beginning of the shift and remains in the same circuit for the entire duration of the shift. The number of trucks that are assigned to a particular shovel is a function of the performance variables of the shovel under question, the desired production level from that shovel, and the expected travel and waiting times for the trucks in the haulage network. There is no changing of assignment during the operation (i.e. locked-in dispatching). Only in the event of a change in the operational conditions such as shovel breakdowns, trucks are reassigned. Due to stochastic nature of haulage operations and random occurrence of down times, formation of long queues at a specific shovel occurs with some frequency.

This strategy has been proven to be the most inefficient. This is mainly due to the fact that the equipment does not operate at constant rate. The reason for this is due to the variation of event times, along with the interactions between trucks at the road intersection points. Furthermore, both trucks and shovels are down for maintenance and servicing. The shovels may sometimes be required to move to new locations during the shift and unpredicted breakdowns may also occur. Under this policy, it is very common to find several trucks waiting in queue at one shovel for loading while another shovel may have been idle for a long time due to the unavailability of trucks. The highest productivity that this system can achieve is when all shovels operate continuously. If one truck is being loaded, the other trucks in the same circuit are either traveling empty or loaded, or are in the process of dumping. This implies efficient operation of the system when trucks are evenly formulated. The study concluded that the comprehensive dispatching criterion took advantage of different criteria and the effect was distinctly better than using a single dispatching rule under various mining conditions.

Temeng et al. (1997) presented a real-time truck dispatching process using a transportation algorithm to implement production maximization and quality control goals. The assignment of trucks is based on the solution to a non-preemptive goal programming model, which determines optimal route production rates and serves as a basis for selecting needy shovels. In the real-time dispatching process, needy shovels are determined by minimizing the deviation of the cumulative production of each route from its targets. Trucks are assigned to needy shovels by a transportation model that minimizes the total waiting time of shovels and trucks. The results showed significant increase in production over fixed dispatching and ensured quality control

Ataeepour and Baafi (1999) developed a stochastic simulation model to analyze the performance of a truck/shovel operation using the Arena software. Arena uses graphical modeling approach as well as animation notion. Systems are typically modeled in Arena using a process orientation. Arena model consists of a graphical representation of the processes where entities (i.e. trucks) move as they progress through the system. They described the main elements of Arena required to perform a truck/shovel simulation and to view the simulation results by means of animation. The layout of the haulage system consisting of five shovels in production faces and three dump sites was generated using the draw tool in Arena.

spread out. It is assumed that the required number of trucks is always available. However, the system often suffers from a lack of trucks due to the high costs involved. The choice of fixed truck assignment strategy may be the result of the evaluation of the operating performance data, such as shovel load and delay times, truck cycle and wait times, production targets, equipment utilizations, etc. This strategy can serve as a baseline by which the effectiveness of other heuristic rules can be measured and it can also be used to validate the simulation model.

3.3 Minimizing Shovel Production Requirement (MSPR)

The objective of this criterion is to achieve the shovel target production, which has been optimized by linear programming or other approaches. When shovels have production targets, a simple heuristic rule is to assign the empty truck at the dispatching point to the shovel which is most behind in its production schedule, taking into account the total capacity of the trucks en route. This rule is most suitable for mines having quality control objectives such as blending requirements. Tan and Ramani (1992) used the following formula for identifying the most lagging shovel.

$$k : \mathrm{argmax}_i \{(\mathrm{TNOW} * \mathrm{PO}_i / \mathrm{TSHIFT}) - \mathrm{P}_i\}, \qquad (3.1)$$

where

k : shovel to which the truck is to be assigned

TNOW: time elapsed from the start of the shift

TSHIFT: total shift time (i.e. 480 minutes)

P_i : actual shovel production at current time

PO_i : shovel target production

The criterion used by Kolonja (1992) is the same, except that actual shovel production explicitly includes capacity of all trucks en route in addition to the trucks already being loaded. In this study, the approach suggested by Kolonja (1992) is used.

It can be seen from the formula that the random features of the network are not taken into consideration and thus the productivity of the system can be improved very slightly. Also, it must be pointed out that several trucks in succession might be sent to the same shovel that is lagging in production due to a breakdown earlier in the shift. This would cause trucks to be queued up at the shovel in question while others may stay idle. Of course, this might be desired if a given target production from each shovel is strictly compulsory on a shift basis for blending purposes. However, this would result in total system production being sacrificed significantly. Tan (1992) claimed that this criterion can guarantee the global optimal solution given by linear programming if the stochastic features of the system can be ignored. Unfortunately, such random impacts are significant in mining operations and cannot be ignored.

To explain this basic heuristic dispatching rule, a simple two shovel example is presented in Table 3.1. It is assumed that one of the shovels is faster than the other and their average loading times are 2 and 3 minutes, respectively. Also, the duration of shift is assumed as 480 minutes. The target production levels for the shovels are expected to be 160 and 240 truck loads, respectively in a shift. Initial truck assignments for the shovels are made at the start of the shift arbitrarily, as 3 and 4 trucks, respectively. If the difference, (B-A), is equal to each other for the two shovels, the truck assignment is made to shovel 1 or shovel 2 arbitrarily.

3.4 Minimizing Truck Waiting Time (MTWT)

In this criterion, an empty truck at the dispatching point is assigned to the shovel which will result in the least truck waiting time for the truck to be loaded by the shovel. The objective of this criterion is to maximize the utilization of both truck and shovels. However, when the number of trucks in the system is relatively small and the trucks do not wait at shovel very often; this rule may result in underutilization of some shovels and, consequently, shovel idle times since several shovels may have zero truck waiting times at the same time. Secondary tie-breaking rules may be necessary for dispatching the trucks and these rules may dominate the overall dispatching decisions. This policy is recommended in mines where specific shovel production targets and grade requirements do not exist.

The decision-making criterion is as follows:

$$k : \arg\min_i \{\max\{SR_i - TR_i\},0\}\}, \qquad (3.2)$$

Table 3.1. An Example Problem for Minimizing Shovel Production Requirement Rule (MSPR)

No	Arrival Time at Dispatching Point, TNOW, (min)	Target Production, STP, (Loads)		Production at Current Time, SP, (Loads)		Number of Trucks On Route, TP, (Loads)		Total Production, A = SP + TP, (Loads)		$B = \frac{TNOW*STP}{TSHIFT}$ (Loads)		Difference, B – A, (Loads)		Shovel Assigned, k: max { B-A}, #	
		Shovel 1	Shovel 2	Shovel 1	Shovel 2	Shovel 1	Shovel 2	Shovel 1	Shovel 2	Shovel 1	Shovel 2	Shovel 1	Shovel 2	Shovel 1	Shovel 2
1	0.0	240	160	0	0	4	3	4	3	-	-	-	-	-	-
2	10	240	160	2	1	2	2	4	3	5	3	1	0	1	-
3	12	240	160	3	2	2	1	5	3	6	4	1	1	1 or 2	1 or 2
4	100	240	160	45	28	3	2	48	30	50	33	2	3	-	2
5	102	240	160	45	28	3	3	48	31	51	34	3	3	1 or 2	1 or 2
6	200	240	160	93	60	2	2	95	62	100	66	5	4	1	-
7	202	240	160	93	60	3	2	96	62	101	67	5	5	1 or 2	1 or 2
8	300	240	160	146	92	1	3	147	95	150	100	3	5	-	2

where

k : Shovel number to which the truck is assigned

SR_i : Ready time of shovel for loading this truck

TR_i : Ready time for the truck to be loaded by the shovel

It should be noted that if (SR_i - TR_i) is greater than zero, then it corresponds to the truck waiting time at shovel i. Truck ready time, (TR_i), is defined as the predicted truck travel time from dispatching point to the shovel and it is determined from the summation of current time, (TNOW), and average truck travel time from the dispatching point to the shovel. Shovel ready time, (SR_i), is defined as the predicted ending time for the shovel to complete loading all the trucks in the queue at shovel including the one being loaded and those that are en route to this shovel, but have not reached yet. Thus, the arrival times of truck on the road should be determined for each shovel. Using these arrival times, a Gantt chart can be constructed for each shovel, which will provide the best estimated shovel ready times for a new truck at the dispatching point. Shovel ready times need to be updated whenever the truck reaches the dispatching point, arrives at or leaves a shovel after loading. Since actual times are unknown at the time of making a dispatching decision, the real-time data recorded should be used for events that are already happened. For the future events, average values should be used to update the shovel Gantt charts (see, Figure 3.1).

The solution to the same example with two shovels (but with different dispatching times) is provided in Table 3.2. Here it is further assumed that the two shovels are separated from each other by a distance of one minute. The mean travel times from the dispatching point to the shovels are 5 and 6 minutes, respectively and the return times from the shovels to the dispatching point are 6 and 7 minutes, respectively. The arrival times of trucks at dispatching point are arbitrarily assumed as 0, 5, 6, 8, 9, 18, 26 and 32 minutes for eight consecutive truck assignments.

When trucks arrive at the shovel, one of two situations may occur: the shovel is idle, hence it starts to load a truck for say 2 minutes on the average, or it is busy causing trucks to wait in queue. If shovel is idle, there is no waiting time for a truck and the shovel immediately loads it. But, if the shovel is busy, the truck waits until it becomes idle. Moreover, all trucks arriving at the shovel enter the queue and await their turn at the shovel. When waiting time is zero, it means that the truck has positioned it and is ready to be loaded at the same time the shovel finished loading the previous truck. Positive waiting times mean that the truck arrived at the shovel, which is still loading another truck. There may or may not be other trucks in the queue. However, negative waiting times mean that the shovel has been idle for a time before the truck arrives. It actually shows the waiting time of the shovel for a truck. In this dispatching policy, the dispatcher estimates both the ready times of this truck at the shovels and the ready times of either shovel to commence loading this truck when it reaches independently. The dispatcher then makes a comparison to select the shovel with the least

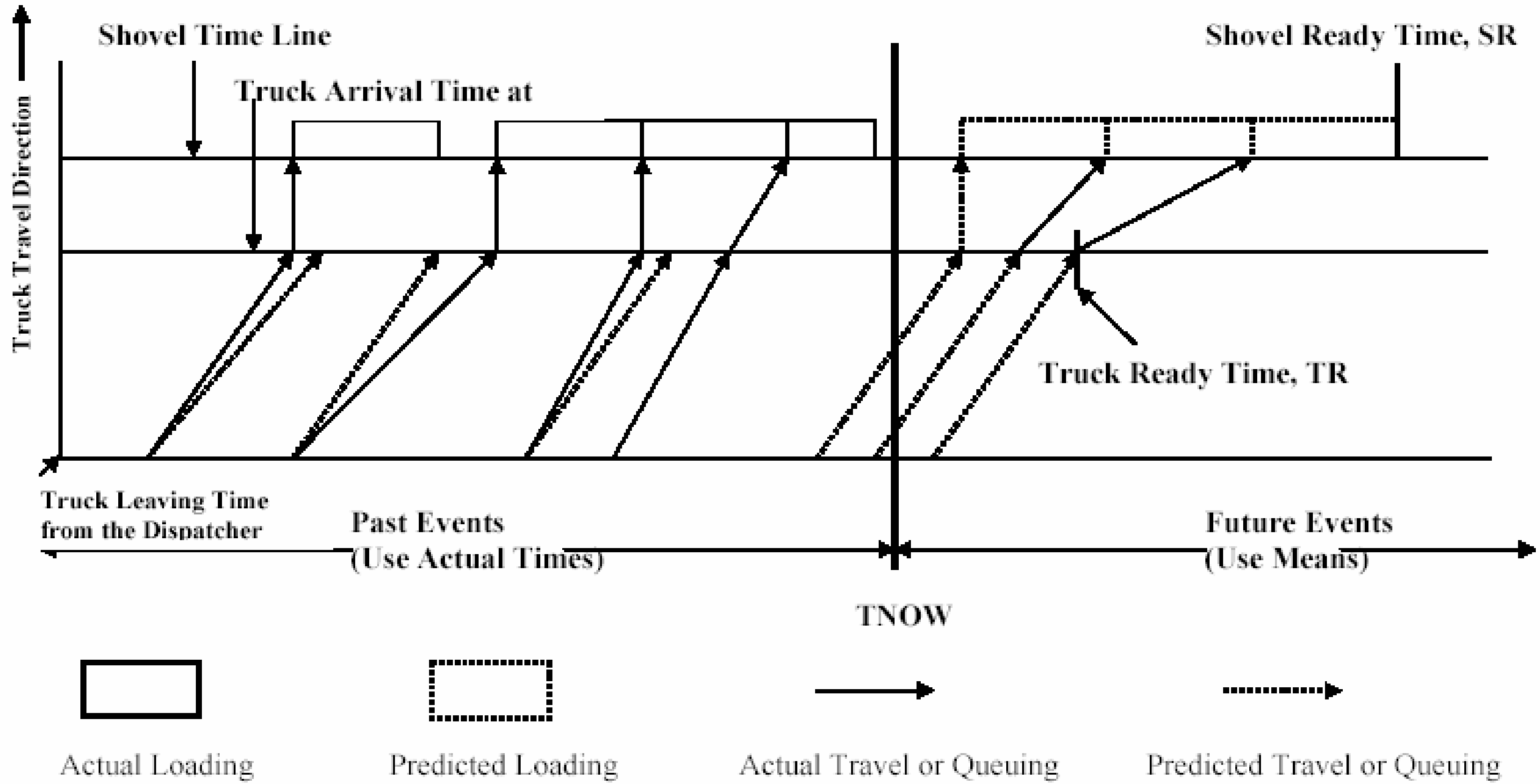


Figure 3.1 An Example of Shovel Loading Gantt Chart

Table 3.2. An Example Problem for Minimizing Truck Waiting Time Rule, (MTWT)

No	Arrival Time at Dispatch Point, TNOW, (min)	Travel Time to Shovel, (min)		Time Joining Shovel Queue		Waiting Time (min)		Time Shovel is Seized		Loading Time (min)		Time Shovel is Released		Shovel Ready Time, SR_i		Truck Ready Time, TR_i		Difference $SR_i - TR_i$		Max $\{SR_i-TR_i,0\}$		Min{ max $\{SR_i-TR_i,0\}$}	Assigned Shovel Number, k
		Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2		
1	0	5	6	5	6	-5	-6	5	6	2	3	7	9	0	0	5	6	-5	-6	0	0	0	1 or 2
2	5	5	6	10	11	-3	-2	10	11	2	3	12	14	7	9	10	11	-3	-2	0	0	0	1 or 2
3	6	5	6	11	12	1	2	12	14	2	3	14	17	12	14	11	12	1	2	1	2	1	1
4	8	5	6	13	14	1	3	14	17	2	3	16	20	14	17	13	14	1	3	1	3	1	1
5	9	5	6	14	15	2	5	16	20	2	3	18	23	16	20	14	15	2	5	2	5	2	1
6	18	5	6	23	24	-5	-1	23	24	2	3	25	27	18	23	23	24	-5	-1	0	0	0	1 or 2
7	26	5	6	31	32	-6	-5	31	32	2	3	33	35	25	27	31	32	-6	-5	0	0	0	1 or 2
8	32	5	6	37	38	-4	-3	37	38	2	3	39	41	33	35	37	38	-4	-3	0	0	0	1 or 2

waiting time. After the minimum waiting time is obtained, the truck is assigned and sent to a particular shovel.

3.5 Minimizing Shovel Waiting Time (MSWT)

In this policy, the empty truck at the dispatching point is assigned to the shovel which has been waiting (longest time) for a truck or is expected to be idle next. The objective of this criterion is to maximize the utilization of shovel by minimizing its waiting time. One of the advantages of this criterion is that it tends to balance out shovel productions more evenly and give results closer to objectives. But, this causes a decrease in the overall production because of the long cycle time required to reach the furthest shovel. This policy is recommended in mines having strict grade requirements even tough is does not optimize production. Moreover, it works better in large open-pit mining operations. If the shovels rarely wait for trucks in under-trucked systems, then secondary tie-breaking rules may be necessary to make the dispatching decisions.

The decision-making criterion is as follows:

$$k : \arg\min_i \{TR_i - SR_i\}, \tag{3.3}$$

where

k : shovel number to which the truck is assigned

SR_i : Ready time of shovel for loading this truck

TR_i: Ready time for the truck to be loaded by the shovel

Table 3.3. An Example Problem for Minimizing Shovel Waiting Time Rule, (MSWT)

No	Arrival Time at Dispatch Point, TNOW, (min)	Travel Time to Shovel, (min)		Time Joining Shovel Queue		Waiting Time (min)		Time Shovel is Seized		Loading Time (min)		Time Shovel is Released		Shovel Ready Time, SR_i		Truck Ready Time, TR_i		Difference TR_i - SR_i		Min{TR_i-SR_i}	Assigned Shovel Number, k
		Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2		
1	0	5	6	5	6	-5	-6	5	6	2	3	7	9	0	0	5	6	5	6	5	1
2	5	5	6	10	11	-3	-2	10	11	2	3	12	14	7	9	10	11	3	2	2	2
3	6	5	6	11	12	1	2	12	14	2	3	14	17	12	14	11	12	-1	-2	-2	1 or 2
4	8	5	6	13	14	1	3	14	17	2	3	16	20	14	17	13	14	-1	-3	-3	1 or 2
5	9	5	6	14	15	2	5	16	20	2	3	18	23	16	20	14	15	-2	-5	-5	1 or 2
6	18	5	6	23	24	-5	-1	23	24	2	3	25	27	18	23	23	24	5	1	0	2
7	26	5	6	31	32	-6	-5	31	32	2	3	33	35	25	27	31	32	6	5	0	2
8	32	5	6	37	38	-4	-3	37	38	2	3	39	41	33	35	37	38	4	3	0	2
9	33	5	6	38	39	1	2	39	41	2	3	41	44	39	41	38	39	-1	-2	-2	1 or 2

It must be pointed out that the travel time to each shovel site is not considered in this dispatching policy. Also, it should be noted that if (TR_i - SR_i) is greater than zero, it corresponds to the shovel waiting time for this truck. The same two shovel example problem is given in Table 3.3.

3.6 Minimizing Truck Cycle Time (MTCT)

In this criterion, the empty truck at the dispatching point is assigned to the shovel which will provide the minimum value for the expected truck cycle time for this truck. The objective of this criterion is to maximize the number of truck cycles during the shift. The truck cycle time (TCT) is a function of mean travel time from dumping point to the shovel to be assigned, waiting time at the shovel after truck's arrival, mean loading time required by the shovel, mean travel time from shovel to the dump point, and the mean truck dumping time.

The decision-making criterion is as follows:

$$k : \arg\min_i \{TCT_i\}, \tag{3.4}$$

where

k : shovel number to which the truck is assigned

TCT_i: truck cycle time for shovel i.

Table 3.4. An Example Problem for Minimizing Truck Cycle Time Rule,

No	Arrival Time at Dispatch Point, TNOW, (min)	Travel Time to Shovel, (min)		Time Joining Shovel Queue		Waiting Time (min)		Time Shovel is Seized		Loading Time (min)		Time Shovel is Released		Shovel Ready Time, SR_i		Truck Ready Time, TR_i		Difference $TR_i - SR_i$		$\text{Min}\{TR_i - SR_i\}$	Assigned Shovel Number, k
		Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2		
1	0	5	6	5	6	-5	-6	5	6	2	3	7	9	0	0	5	6	5	6	5	1
2	5	5	6	10	11	-3	-2	10	11	2	3	12	14	7	9	10	11	3	2	2	2
3	6	5	6	11	12	1	2	12	14	2	3	14	17	12	14	11	12	-1	-2	-2	1 or 2
4	8	5	6	13	14	1	3	14	17	2	3	16	20	14	17	13	14	-1	-3	-3	1 or 2
5	9	5	6	14	15	2	5	16	20	2	3	18	23	16	20	14	15	-2	-5	-5	1 or 2
6	18	5	6	23	24	-5	-1	23	24	2	3	25	27	18	23	23	24	5	1	0	2
7	26	5	6	31	32	-6	-5	31	32	2	3	33	35	25	27	31	32	6	5	0	2
8	32	5	6	37	38	-4	-3	37	38	2	3	39	41	33	35	37	38	4	3	0	2
9	33	5	6	38	39	1	2	39	41	2	3	41	44	39	41	38	39	-1	-2	-2	1 or 2

Clearly, this criterion is strongly affected by the value of the truck cycle time and the overall resulting effect is that more trucks are assigned to the shovels closer to dispatching point. The solution to the same two shovel example is given in Table 3.4. Here, it must be mentioned that the expected truck waiting times are arbitrarily assumed to have the values provided in Table 3.4. But, they are estimated from respective shovel Gantt charts in simulation program.

3.7 Minimizing Shovel Saturation or Coverage (MSC)

In this criterion, the empty truck at the dispatching point is assigned to the shovel which has the least degree of saturation among the available shovels. The objective of this rule is to assign the trucks to the shovels at equal time intervals to keep a shovel operating without waiting for trucks. The degree of saturation is defined as the ratio between the number of trucks that have been assigned and the desired number of trucks that should have been assigned to the shovel under consideration. The desired number, also referred to as the saturation number, is the number of trucks given by the ratio of the average travel time for the truck from the dispatching point to the shovel to the average shovel loading time for the truck.

The decision-making criterion is as follows:

$$k : \arg\min_i \{(SR_i - TNOW) / TT_i\}, \tag{3.5}$$

where

k : Shovel number to which the truck is assigned

SR_i : Ready time of shovel for loading this truck

TNOW: Time elapsed from the start of shift

TT_i : Mean travel time from dispatching point to the shovel to be assigned.

This dispatching criterion attempts to utilize all the shovels in the system evenly and at the same time, keeps a balance between the truck requirements. This dispatching policy would be desirable in mines with a relatively sufficient number of available trucks to meet the shovel requirements. The same two shovel example problem is given in Table 3.5.

3.8 Earliest Loading Shovel (ELS)

In this criterion, the empty truck at the dispatching point is assigned to the shovel where it is expected to be loaded at the earliest future point in time. This rule tends to reduce truck idle time and prevent long waiting lines. It might result in unbalanced production among the shovels since it encourages dispatching trucks to closer shovels. This might occur seriously if the system is undertrucked. The solution to the example problem is given in Table 3.6.

The decision-making criterion is as follows:

$$k : \arg\min_i \{\max\{TR_i, SR_i\}\}, \tag{3.6}$$

where

k : shovel number to which the truck is assigned

Table 3.5. An Example Problem for Minimizing Shovel Coverage Rule, (MSC)

No	Arrival Time at Dispatch Point, TNOW, (min)	Travel Time to Shovel, TT_i (min)		Loading Time, LT_i (min)		Truck Return Time, RT_i, (min)		Expected Truck Waiting Time, WT_i (min) (assumed)		Truck Cycle Time, $TCT_i = TT+RT+LT+WT$ (min)		$Min\{TCT_i\}$ (min)	Assigned Shovel Number, k
		Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2		
1	0	5	6	2	3	6	7	3	0	16	15	15	2
2	5	5	6	2	3	6	7	2	1	15	16	15	1
3	6	5	6	2	3	6	7	1	2	14	17	14	1
4	8	5	6	2	3	6	7	4	1	17	16	16	2
5	9	5	6	2	3	6	7	5	2	18	17	17	2
6	18	5	6	2	3	6	7	4	2	17	17	17	1 or 2
7	26	5	6	2	3	6	7	2	3	15	18	15	1
8	32	5	6	2	3	6	7	0	2	13	17	13	1
9	33	5	6	2	3	6	7	1	3	14	18	14	1

SR_i : Ready time of shovel for loading this truck

TR_i : Ready time for the truck to be loaded by the shovel

In this dispatching criterion, the distances between the dispatching point and the shovels have significant effect over the dispatching results.

3.9 Longest Waiting Shovel (LWS)

In this criterion, the empty truck at the dispatching point is assigned to the shovel which has been waiting for a truck longest. The objective of this policy is to balance the production among the shovels.

The decision-making criterion is as follows:

$$k : \arg\max_i \{\max\{TR_i - SR_i\},0\}\}, \qquad (3.7)$$

where

k : Shovel number to which the truck is assigned

SR_i : Ready time of shovel for loading this truck

TR_i : Ready time for the truck to be loaded by the shovel

Table 3.6. An Example Problem for Earliest Loading Shovel Rule, (ELS)

No	Arrival Time at Dispatch Point, TNOW, (min)	Travel Time to Shovel, (min)		Time Joining Shovel Queue		Waiting Time (min)		Time Shovel is Seized		Loading Time (min)		Time Shovel is Released		Shovel Ready Time, SR_i		Truck Ready Time, TR_i		Max $\{TR_i, SR_i\}$		Min{ max{TR_i, SR_i}}	Assigned Shovel Number, k
		Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2		
1	0	5	6	5	6	-5	-6	5	6	2	3	7	9	0	0	5	6	5	6	5	1
2	5	5	6	10	11	-3	-2	10	11	2	3	12	14	7	9	10	11	10	11	10	1
3	6	5	6	11	12	1	2	12	14	2	3	14	17	12	14	11	12	12	14	12	1
4	8	5	6	13	14	1	3	14	17	2	3	16	20	14	17	13	14	14	17	14	1
5	9	5	6	14	15	2	5	16	20	2	3	18	23	16	20	14	15	16	20	16	1
6	18	5	6	23	24	-5	-1	23	24	2	3	25	27	18	23	23	24	23	24	23	1
7	26	5	6	31	32	-6	-5	31	32	2	3	33	35	25	27	31	32	31	32	31	1
8	32	5	6	37	38	-4	-3	37	38	2	3	39	41	33	35	37	38	37	38	37	1
9	33	5	6	38	39	1	2	39	41	2	3	41	44	39	41	38	39	39	41	39	1

Table 3.7. An Example Problem for Longest Waiting Shovel Rule, (LWS)

No	Arrival Time at Dispatch Point, TNOW, (min)	Travel Time to Shovel, (min)		Time Joining Shovel Queue		Waiting Time (min)		Time Shovel is Seized		Loading Time (min)		Time Shovel is Released		Shovel Ready Time, SR_i		Truck Ready Time, TR_i		Difference $TR_i - SR_i$		Max $\{TR_i - SR_i, 0\}$		Max{ max{TR_i-SR_i, 0}}	Assigned Shovel Number, k
		Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2	Sh 1	Sh 2		
1	0	5	6	5	6	-5	-6	5	6	2	3	7	9	0	0	5	6	5	6	5	6	6	2
2	5	5	6	10	11	-3	-2	10	11	2	3	12	14	7	9	10	11	3	2	3	2	3	1
3	6	5	6	11	12	1	2	12	14	2	3	14	17	12	14	11	12	-1	-2	0	0	0	1 or 2
4	8	5	6	13	14	1	3	14	17	2	3	16	20	14	17	13	14	-1	-3	0	0	0	1 or 2
5	9	5	6	14	15	2	5	16	20	2	3	18	23	16	20	14	15	-2	-5	0	0	0	1 or 2
6	18	5	6	23	24	-5	-1	23	24	2	3	25	27	18	23	23	24	5	1	5	1	5	1
7	26	5	6	31	32	-6	-5	31	32	2	3	33	35	25	27	31	32	6	5	6	5	6	1
8	32	5	6	37	38	-4	-3	37	38	2	3	39	41	33	35	37	38	4	3	4	3	4	1
9	33	5	6	38	39	1	2	39	41	2	3	41	44	39	41	38	39	-1	-2	0	0	0	1 or 2

It must be noted that if (TR_i- SR_i) is greater than zero, it corresponds to the shovel waiting time for this truck. This rule is generally preferred if the number of trucks in the system is small. If the number of trucks in the system is large, secondary rules will be required to make the truck assignment decisions. The solution to our example problem is given in Table 3.7.

3.10 Adaptive Rule (AR)

In this study, a general combined truck dispatching criterion is developed following the comprehensive analysis and comparison of various basic dispatching criteria presented above. The combined criterion, also called as adaptive rule, applies a procedure to dispatch the trucks at the dispatching point by utilizing the standardized utilization of both shovels and trucks. The standardized truck utilization is defined as the ratio of the difference between the current truck utilization and the mean truck utilization divided by the standard deviation of truck utilization. Similarly, the standardized shovel utilization is defined as the ratio of the difference between the current shovel utilization and the mean shovel utilization divided by the standard deviation of shovel utilization. That is;

$$STU = \frac{TU_{cur} - TU_{mean}}{SDTU}, \tag{3.8}$$

where

STU : Standardized truck utilization

TU_{cur} : Current truck utilization

TU_{mean} : Mean truck utilization

SDTU : Standard deviation of truck utilization

and

$$SSU = \frac{SU_{cur} - SU_{mean}}{SDSU},$$

(3.9)

where

SSU : Standardized shovel utilization

SU_{cur} : Current shovel utilization

SU_{mean} : Mean shovel utilization

SDSU : Standard deviation of shovel utilization

This adaptive rule tries to achieve a balance between two dynamic system performance measures, (i.e. truck utilization and shovel utilization). The decision-making criterion selects one of the two basic dispatching rules that have the best performances for the given performance measures. The two best performing basic rules are selected from among the eight basic heuristic policies mentioned above by using the results of statistical analysis of simulation experiments. Table 3.8 gives an example for the adaptive dispatching rule. In this example, it is assumed that the shovel has mean utilization of 0.60 and the standard deviation of the shovel utilization is 0.10. Also, the mean truck utilization is taken as 0.70 and the standard deviation of truck utilization is assumed to be 0.15. For each truck dispatching decisions, the difference between standardized shovel utilization and standardized truck utilization is determined. If this difference is greater than zero, one of the two basic rules, say, minimizing shovel coverage (MSC) is applied. If it is less than zero, another rule (i.e. earliest loading shovel, ELS) is applied. The current shovel and truck utilizations are updated after each truck assignment.

Table 3.8 An Example Problem for Adaptive Dispatching Rule (AR)

Dispatching Time, TNOW	Current Shovel Utilization, SU_{cur}	Current Truck Utilization, TU_{cur}	Mean Shovel Utilization, SU_{mean}	Mean Truck Utilization, TU_{mean}	Standard Deviation for Shovel, Utilization SDSU	Standard Deviation for Truck Utilization, SDTU	Standardized Shovel Utilization, SSU	Standardized Truck Utilization, STU	Difference, SSU – STU	Rule Applied (ELS or MSC)
50	0.75	0.85	0.60	0.10	0.70	0.15	1.50	1.00	0.50	MSC
100	0.80	0.80	0.60	0.10	0.70	0.15	2.00	0.67	1.33	MSC
150	0.70	0.87	0.60	0.10	0.70	0.15	1.00	1.13	-0.13	ELS
200	0.69	0.90	0.60	0.10	0.70	0.15	0.90	1.33	-0.43	ELS
250	0.71	0.88	0.60	0.10	0.70	0.15	1.10	1.20	-0.10	ELS
300	0.75	0.83	0.60	0.10	0.70	0.15	1.50	0.86	0.64	MSC
350	0.80	0.80	0.60	0.10	0.70	0.15	2.00	0.67	1.33	MSC
400	0.75	0.85	0.60	0.10	0.70	0.15	1.50	1.00	0.50	MSC
450	0.70	0.90	0.60	0.10	0.70	0.15	1.00	1.33	-0.33	ELS
475	0.69	0.85	0.60	0.10	0.70	0.15	0.90	1.00	-0.10	ELS

CHAPTER 4

SIMULATION MODELS

4.1 Introduction

This chapter deals with a detailed description of the input data set components, basic modeling assumptions made and the general structure of the simulation program. The input data are one of the most important aspects in the implementation of any simulation study. The modeling of open pit haulage systems using computer simulation has been in widespread use for many years. The models have been developed in a variety of ways including time study data, calculation based on manufacturers' performance curves and real time data generated by computerized truck dispatching systems.

In the time study approach, the individual times of various movements and operations are recorded. For example, the time it takes a certain type of haulage unit to traverse a haul road segment is measured directly by an observer in the field. Travel times for each truck type, both loaded and empty, are required for each road segment. Similarly, loading and dumping times are required for each truck type for various shovels and dump points. During simulation process, trucks are cycled through the haulage network following a series of dispatching rules regarding shovel assignment. When a truck enters a road segment, it is randomly assigned a travel time based on the time study data. This is known as Monte Carlo simulation because of the random way the data is selected. The procedure is simple and the simulation process moves trucks through a network according the underlying rules selected. A computer simulation program performs these tasks quickly and keeps track of the required output statistics. However, time study based simulation has several major disadvantages relating to the conditions and the configurations of the haulage road network. These studies are useful when selecting equipment for a new mine. The configuration of the haulage road network change frequently and maintaining current data are time consuming and impractical if the data are collected manually. Estimating travel times through a calculation procedure is preferable in these cases. Modern computer dispatch systems keep continuous track of vehicle movements and create a real time computer database of haulage fleet movements. This could provide a powerful method of updating the model based on current shovel locations, road conditions, etc.

In developing a computerized truck dispatching model, it is necessary to acquire detailed information related to the haulage system. An accurate assessment of the actual working of the haulage system and the sequence of events are essential. All these data project a finite picture of the exact problem involved and this gives an idea of the components that need to be simulated. The technique of simulation characterizes the system in terms of its components and a set of rules relating the interactions between these components. Hence, the model is defined by this set of rules and the components, namely trucks and shovels, each with its own characteristics.

The simulation program developed in this study is designed with the objective of studying the effects on productivity by continuously dispatching trucks in medium-sized open pit mine under various heuristic policies. Although the simulation program is developed primarily to test the dispatching procedures, several problems related to an open pit mine operation can also be solved. Prior to making a large capital expenditure for loading and haulage equipment, there is an evident need for careful evaluation of possible combination of shovels and trucks and haul road configurations in the light of planned production requirements in order to achieve minimum production cost. Hence, it is possible to determine the equipment requirements according to the productivity obtained with each shovel/truck combination, evaluation of equipment replacements and testing different haulage layouts in order to determine best possible haulage network.

The model developed should be simple to use but, at the same time should adequately duplicate the real operations to be credible. The economic feasibility of using a truck dispatching system in an open pit operation is also very crucial. The selection of dispatching policies is done according to the objectives of a particular operation, which may change with time. The mine management should decide which dispatching procedure is to be used in a specific mine. For example, minimizing truck waiting time rule (also called maximizing truck use) yields consistently higher fleet production. But, it may not be useful when the operation requires grade control or when the differences in truck travel times between shovels is large. In general, it is more desirable to have all the operating shovels working at the same rate (i.e. utilization). The success of a dispatching procedure depends to a great extend upon the number of truck operating in the total range from undertrucked to overtrucked situations. The major purpose of providing a dispatching system is to maximize productivity of the system. This can be done through procedure such as maximizing either truck or shovels utilizations.

4.2 Basic Assumptions

The following basic modeling assumptions are made in the simulation program for the open pit truck/shovel haulage system developed in this study.

1. All trucks in the mine are the identical (i.e. their capacity, motor power, speed, etc are the same).
2. All shovels in the mine are identical in terms of their loading capabilities (i.e. they have the same probability distribution types and same parameters for loading process).
3. The mine haul roads are designed to provide two-way traffic for the trucks.
4. More than one truck can travel along different roads (i.e. trucks are allowed to overtake each other along the haul roads).
5. All shovels and the dumping site can serve only one truck at a time and trucks may form queues at the dumping point.
6. Single material type is assumed for the simulation program and all trucks in the mine dump their loads at the same dumping site.
7. All trucks start operation at the parking area near the dumping point at the start of the shift and park there at the end of each shift.

8. During a simulation run, the haulage system is performing without any rest (i.e. eight hours per shift).
9. In modeling the breakdowns of trucks, all trucks are only checked out for failure after dumping their loads at the dumping area during a shift.
10. In modeling the breakdown of shovels, all trucks that are previously dispatched to a shovel which is in failure mode remain in the same circuit until it is replaced by a standby shovel and it is further assumed that there is a sufficient supply of standby units available at the mine. Furthermore, trucks are not dispatched to this shovel location until it is replaced by another shovel.

4.3. Input Data

When performing a stochastic simulation study, the sources of randomness for the system under consideration must be represented properly. In many simulation studies, little attention has been paid to the process of selecting input probability distributions. In a simulation study such as the analysis of truck dispatching criteria, proper modeling of individual events is crucial to obtain meaningful results. Since random samples from input probability distributions drive a simulation model of a real system through time, basic simulation output data or an estimated performance measure computed from them are also random. Therefore, it is important to model system randomness correctly with appropriate probability distributions. It must be emphasized that the technique of simulation is the most practical method used for producing experimental data necessary for conducting different operating policies in open-pit mines.

One of the most important aspects of any simulation model is the reliability of the results produced. This is a function of the accuracy of input data collected. Thus, the importance of time studies to be carried out must be realized in order to decide on how much of the real system must be represented in the model. The best simulator is only as good as the input data it receives (Tu and Hucka, 1985). The input data are very difficult to generalize in order for the model to be universally applicable. Every mine is different in truck fleet size and type, shovel size and type, number of crushers and dumps, configuration of haulage networks, etc. Most mines operate with multiple types of shovels and trucks and with different operational policies so that it is impossible to define a general input data set for the simulation model.

In time study operations, it is very important to clearly define the duration of each event component and ensure that the definition of the events are the same no matter who conducts the time study. Basically, the truck/shovel operations are observed through the following six event components:

1. Truck loading (time): it is the total time it takes to load a truck. This time starts at the moment the shovel starts digging and ends when the shovel operator gives a signal indicating the completion of the loading activity.

2. Spotting (time) at the shovel: this time starts from the moment the truck leaves its queue position and moves towards the shovel to the moment it achieves the position for loading.
3. Spotting (time) at dump: this time starts from the moment the truck begins motion from its queue position towards the dump to the moment it achieves the position for dumping.
4. Dumping (time): the dumping time starts from the moment a truck initiates unloading to the moment the truck begins to move away from the berm after dumping its load.
5. Truck full travel (time): it starts at the time the shovel operator gives a signal and ends when the truck reaches the dump point or starts to wait in the queue at the dump.
6. Truck empty travel (time): this time starts at the end of the dumping operation and ends when the truck reaches the shovel or starts waiting in the queue in front of the shovel.

Outliers, which are defined as those data values that do not belong to the same population as the bulk of the observed data, are one of the serious problems in dealing with real operational data collected from time studies. There is no proven rule to determine which observed values are outliers. Tu and Hucka (1985) suggest, as a rule of thumb, that all data values should be included within plus or minus 3.5 standard deviations of the mean. All data collected from time studies for the truck/shovel systems should be non-negative, that is, the values must be greater than zero.

In this study, the spotting (time) at shovels is included in the waiting time at the shovel, and the spotting (time) at dump is included in the waiting time at the dump point if the truck has to wait or in the truck full travel (time) if the truck is immediately served by the shovels. The input data to be used in the simulation programs are not taken from a real open pit mine. Instead, it is taken from literature values that are most commonly used. That is, the simulation model is developed for a hypothetical open pit mine. Normal distribution is selected for all of the random variables, namely for truck loading (times) at shovels, truck traveling (times) both loaded and empty, dumping (times) at dump. The parameters used for the random variables are arbitrarily assumed and are given in Table 9.1. Exponential distribution is used for modeling the breakdowns of shovels and trucks. The parameters used for the random variables are arbitrarily assumed and are given in Table 9.2. The reason for this is the familiarity of these two distributions and their common use in modeling open pit haulage systems. However, any other distribution can be used for any random variable in the models with small changes to the programs easily.

Table 4.1 Parameters for the Random Variables Used in the Models (minutes)

Random Variables	Standard Deviation		Mean
	Low	High	
Loading Times	0.25	0.50	2.50
Dumping Times	0.15	0.15	1.00
Truck Full Travel time	0.50	1.00	5.50
Truck Empty Travel Time	0.40	0.80	4.50

Table 4.2 Parameters for Equipment Down-Times and Working Times Used in the Models (minutes)

Random Variable	Mean
Time Between Truck Down-times	45.0
Truck Down-times	5.0
Time Between Shovels Down-times	40.0
Shovel Down-times	10.0

4.4 Basic Model Structure

Sound modeling complex systems requires a detailed knowledge of both the simulation language and the system under study. In the execution of a truck dispatching model, the most important part is the simulation of the system. When simulating a truck/shovel operation, it is essential that the method used be precise and reliable. Modeling of truck movement in conjunction with shovel productivity is the most critical aspects of the simulation program. The entire decision-making process is affected by the expected equipment performances. Simulation software should be selected based on how well it is suited to the scope and the level of detail of the specific model to be developed. There are many software tools such as SIMAN (Arena), SLAM II, GPSS/H, AutoMod etc. available in the market which enables a simulation modeler to develop models with greater complexity. They provide excellent environment to the simulation modelers so that any complex model can be developed and programmed easily with greater flexibility in short period of time as compared to the most general-purpose programming languages such as FORTRAN or C.

The simulation program developed in this study is written in GPSS/H simulation language, which is a discrete-event simulation model. The general structure of the main simulation model is shown in Fig. 4.1. Systems are modeled in GPSS/H software using only the process-interaction approach of the discrete-event simulation modeling. A GPSS/H model resembles the structure of a flow chart of the system being modeled. This intuitive modeling approach contributes greatly to the ease and speed with which simulation models can be built. After the model has been built, the process representation is executed by GPSS/H and the activities of entities are automatically controlled and monitored. Models are developed in text files and subsequently compiled directly into memory and executed in GPSS/H. The modeler specifies the sequence of events, separated by lapses in time, which describes the manner in which entities flow through the system. As shown in Figure 4.2, the computer model represents the basic truck operations in terms of events such as loading, dumping, hauling etc.

In process-interaction approach, models are constructed as block diagrams, which are linear top-down flow graphs depicting the flow of entities through the system. The term process denotes the sequence of operations or activities through which entities can move. For example, a process in a truck-shovel system may consist of a loading operation, hauling operation, dumping operation and returning from the dump site. The entities in the model are used to represent shovels, trucks, information about equipment breakdowns, dispatching logic, etc. which occur in a real truck/shovel system. The representation of entities in GPSS/H is called transactions. GPSS/H models typically contain at least one GENERATE block to create transactions into the model and one or more TERMINATE blocks that model the departure of these transactions from the model. However, in a truck-shovel haulage system, one transaction is created for each truck entity at a single GENERATE block and they do not depart from the system. But, they would rather move through the system cyclically. Such a truck-shovel system can be depicted as in Figure 4.3. In GPSS/H, transactions (i.e. trucks) move from one block to another in a block diagram representing sequence of events which may change the state of the system to perform the required operations. For example, when a truck transaction moves into a SEIZE block, it will change the state of the queue and the resource defined by that block. Figure 4.4 shows the layout of a typical truck-shovel mining system, which consists of five shovels in production faces and a single dumping site where materials from all of the shovels are dumped. Trucks are dispatched to new destinations at the dispatching point after dumping their loads at dumpsite.

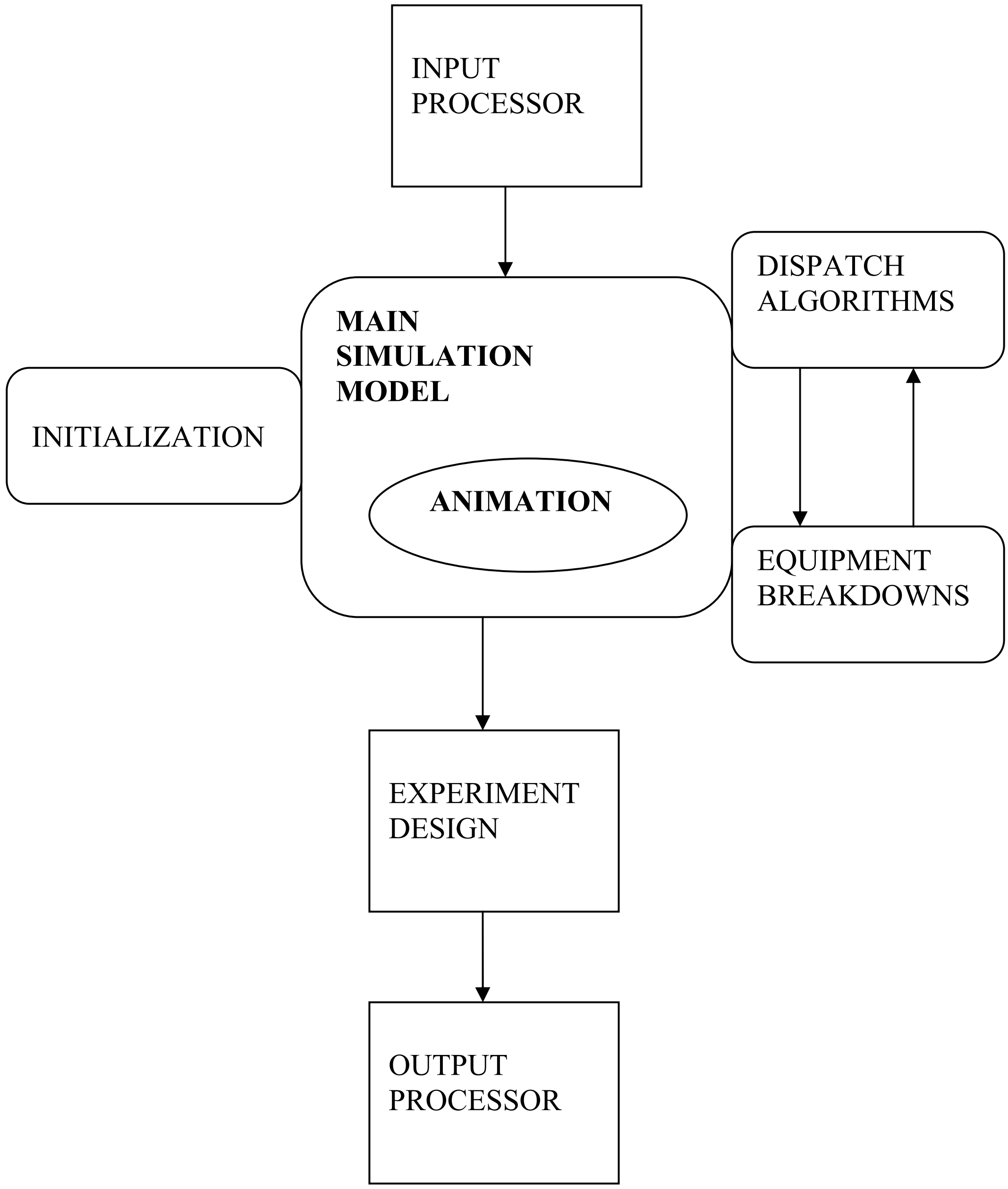


Figure 4.1 General Structure of the Simulation Model

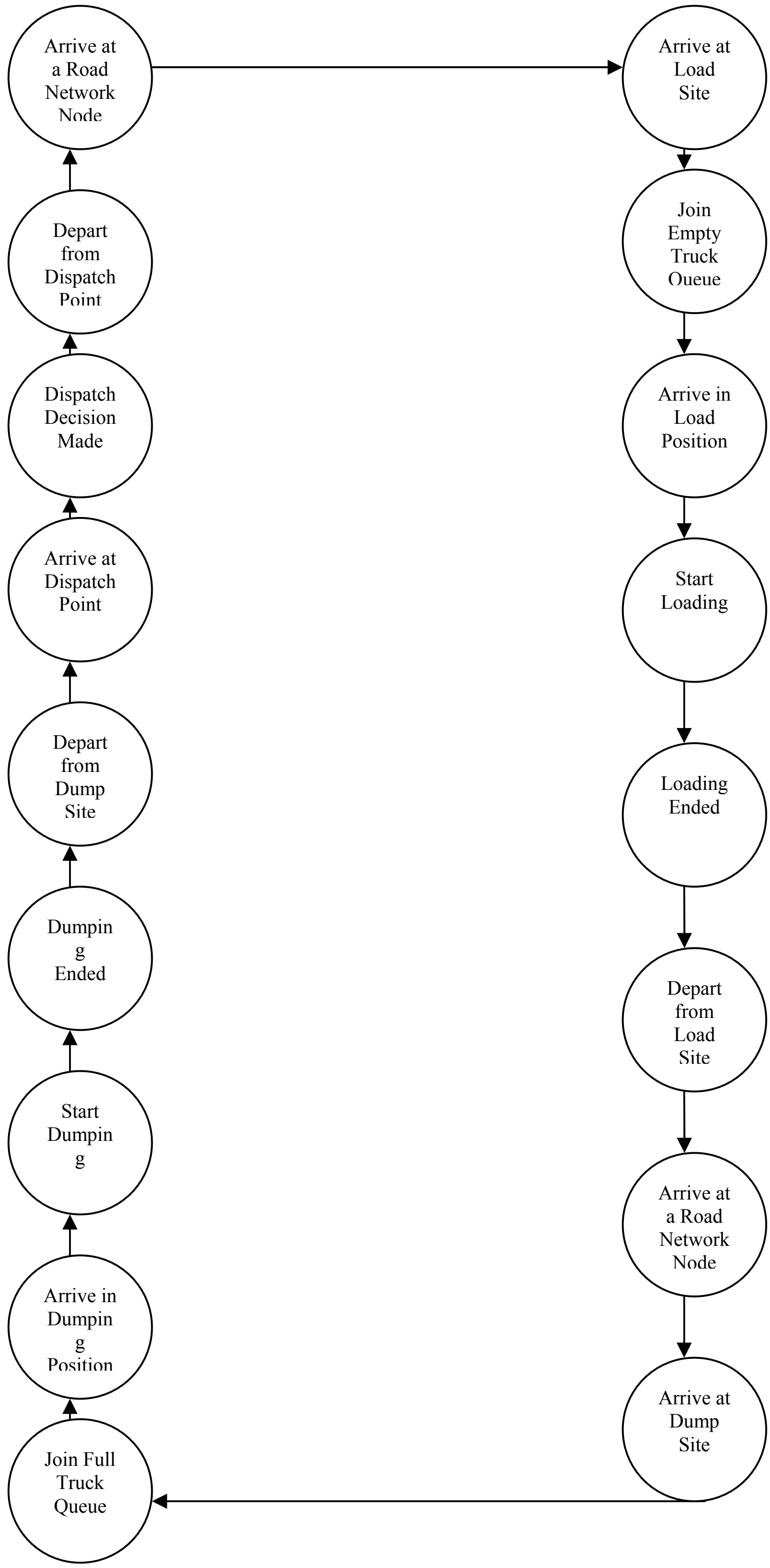


Figure 4.2 Event Sequence for Truck Haulage Model

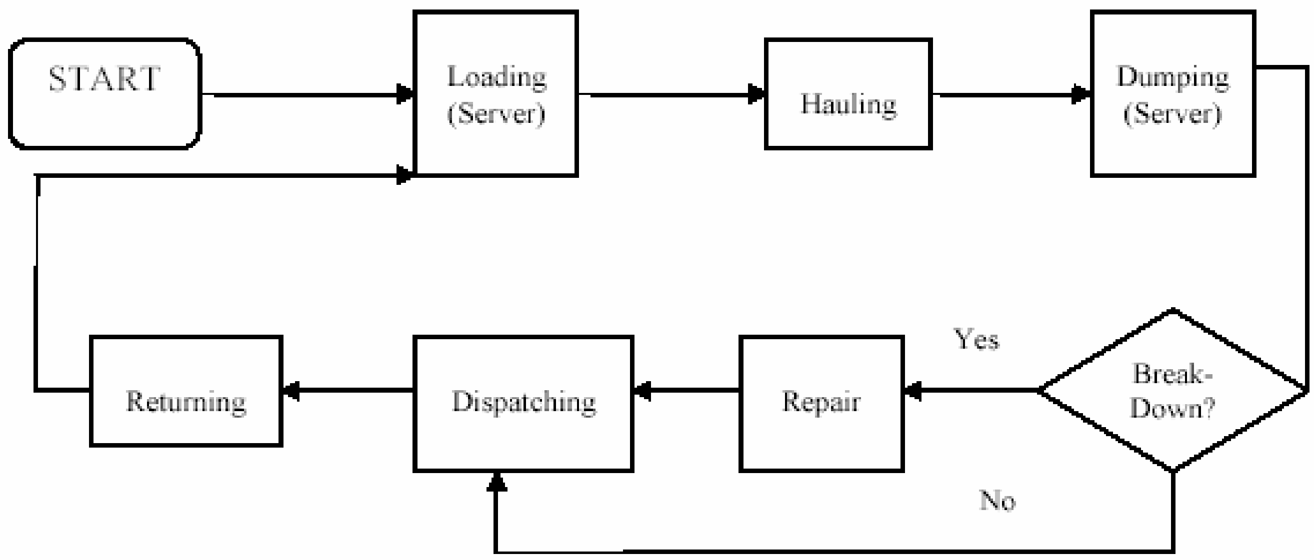


Figure 4.3 Truck-Shovel System Modeling Concepts

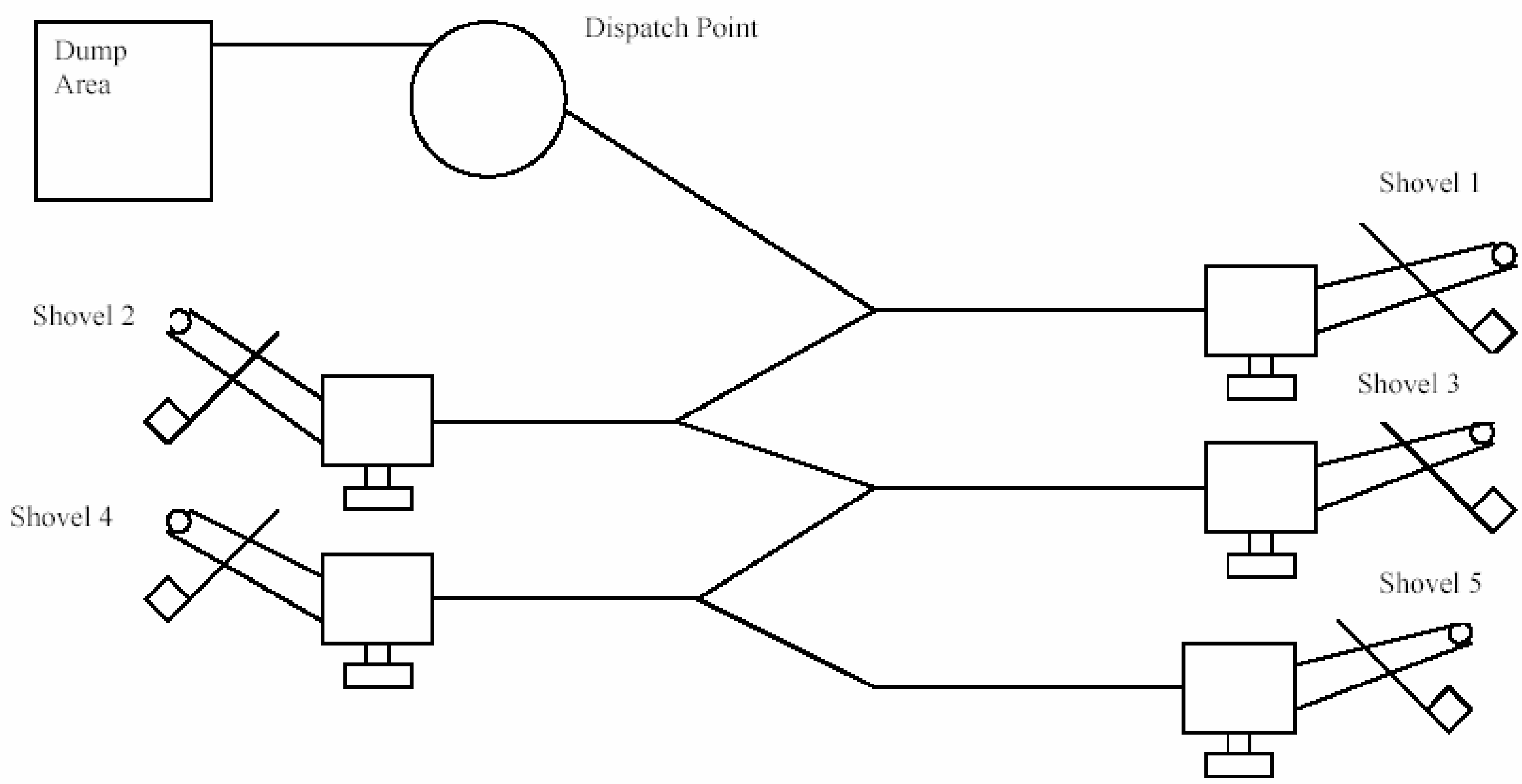


Figure 4.4 A Typical Truck-Shovel Mining System

CHAPTER 5

EXPERIMENTAL RESULTS AND DISCUSSIONS

5.1 Introduction

Truck dispatching policy is usually concerned with the specific loading-haulage-dumping system configuration in an open pit mine. The location of shovels and dumps and the distances between them and the network of haulage roads connecting affect the performance of mining equipment significantly. Truck dispatching algorithms based on heuristic rules are easier to implement and do not require much computation when making dispatch decisions in real-time. Simulation models of open pit truck/shovel haulage systems have many significant advantages. It deals with the passage of time, random occurrences and interaction of multiple activities. The intent of a simulation model is to emulate an actual operating system. Experiments can then be conducted on this model to determine the effects of altering model parameters on performance measures. Conducting experiments on an actual operating system is typically infeasible or impractical. For example, buying the wrong piece of new mining equipment can be very expensive in both time and money. The ability to experiment on a representative model can yield information that is not obtainable in a reasonable amount of time. Simulation model provides this ability. When it is impractical to experiment with the actual system, it is required to use the simulation model and the design of experiments to form a very powerful analysis tool. In general, the objectives of simulation experiments are to:

- Obtain knowledge of the effects of controllable factors on the experimental outputs
- Estimate system parameters of interest
- Make a selection from among a set of alternatives and
- Determine the treatment levels for all the factors which produce an optimum response.

The experimental design specifies the combination of the treatment levels along with the number of replications for each combination for which the simulation must be performed. Because of the random nature of simulation input, a simulation run produces a statistical estimate of the true performance measure, not the measure itself. In order for an estimate to statistically precise and free of bias, the analyst must specify for each system of interest appropriate choices for the following:

1. Length of each simulation run
2. Number of independent simulation runs
3. Length of the warm-up period, if one is appropriate

It is recommended that always at least 3-5 independent runs are made for each system design, and using the average of the estimated performance measures from the individual runs as the overall estimate of the performance measure. This overall estimate should be more statistically precise than the estimated performance measure from one run. Also, independent runs are required to obtain legitimate and simple variance estimate and confidence intervals.

The simulation experiments are made to investigate the effects of basic heuristic truck dispatching rules for an open pit truck/shovel haulage operations by changing the total number of trucks as the controllable input variable while all other system variables being fixed. That is, only one variable at a time is varied to make the experiments. In experimental design terminology, the input parameters and the structural assumptions composing a model are called the factors and the output performance measures are called as responses. A simulation run is an experiment in which an assessment of the performances of a system can be estimated for a prescribed set of conditions. The factors are set at different levels called treatments in the experiment. The design of experiments method describes a recipe for setting the factors and levels in the experiment and a method for analyzing the results. When the experiments are run and the response (i.e. performance measures) data are collected, the effects of factors on the performance measures and the interaction between them can be determined to evaluate the results obtained from simulation experiments using Analysis of Variance (ANOVA) procedures. The three performance measures selected in this study include total truck productions in truckloads (TP), overall truck utilization (TU) and overall shovel utilization (SU). The factors investigated are truck dispatching rules selected (DR), the number of shovels operating (S), the number of trucks operating (NT), the variability in truck loading times (LT), the variability in truck hauling times (HT), the variability in truck return times (RT), the location of shovels with respect to dumping area (SDD) and the availability of shovel and truck resources (A). Eight different basic dispatching rules are investigated in this study for each case scenario. In this study, the simulation experiments were designed to study the effects of several factors at two stages:

1. Experiment 1 (with eight heuristic dispatching rules)
2. Experiment 2 (with adaptive rule and basic rules in Experiment 1).

5.2 Experiment 1

In this study, the simulation experiments were designed to study the effects of;

- Heuristic dispatching rules
- Number of shovels operating
- Number of trucks operating
- Distance between the shovels and the dumping site
- Variability in truck loading times
- Variability in truck hauling times
- Variability in truck return times
- Availability of truck and shovel resources

on the performances of truck and shovel resources. Truck and shovel performances were determined by selecting the total truck productions (in truck loads), overall truck utilization and overall shovel utilization. The simulation model which was developed in this study and explained in Chapter 4 were run to obtain the output data necessary to be used for analyzing relationship between the factors and responses.

5.2.1 Factors

The following parameters were considered to study the effects of main factors on the truck and shovel performances.

a) Truck dispatching rules: Eight different basic heuristic truck dispatching rules and an adaptive rule described in Chapter 3 were modeled separately for each case and experimented by running the simulation models. Each basic rule was considered as a different level or treatment in the experimental design.

b) Number of operating shovels: The number of operating shovels was selected as 3, 4 and 5 considering the case for a typical medium-sized open pit mine.

c) Number of operating trucks: The number of operating trucks was taken as 9, 15 and 21 trucks considering the cases for undertrucked, match number and overtrucked conditions for three shovels operation, respectively.

d) Distance between the shovels and the dumping site: The distance between the shovels and the dumping site were taken to be as either

- all shovels at the same distance to the dumping site or
- 1-minute separation between each shovel from the dumping site.

e) The variability in truck loading times: Normal distribution with a mean of 2.5 minutes was used in all of the simulation runs for truck loading times. The variability in truck loading times was tested by changing the standard deviation of the normal distribution and has either

- Low (0.25 minutes) or
- High (0.50 minutes) variability.

f) The variability in truck hauling times: Normal distribution with a mean of 5.5 minutes was used in all of the simulation runs for truck hauling times. The variability in truck hauling times was tested by changing the standard deviation of the normal distribution and has either

- Low (0.50 minutes) or
- High (1.00 minutes) variability.

g) The variability in truck return times: Normal distribution with a mean of 4.5 minutes was used in all of the simulation runs for truck return times. The variability in truck return times was tested by changing the standard deviation of the normal distribution and has either

- Low (0.40 minutes) or
- High (0.80 minutes) variability

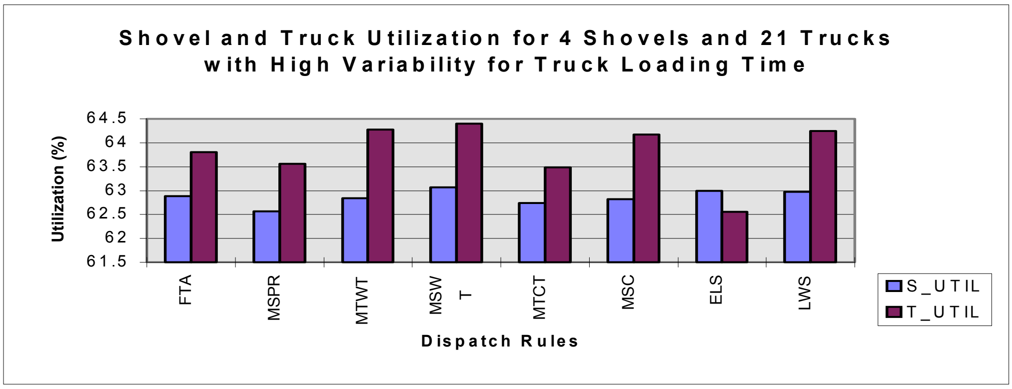
h) The availability of shovel and truck resources: Exponential distribution was selected to model the breakdown of both equipment types. The mean time between failures (MTBF) was taken as 40 and 45 minutes in a shift for the shovels and trucks, respectively and the mean time to repair (MTTR) was taken as 10 and 5 minutes in a shift for the shovels and trucks, respectively. The availability of shovel and trucks were set at 2 levels as either

- 100 % availability for both shovels and trucks (i.e. without breakdown) and
- Overall availability of 90 % for trucks and 85 % for shovels (i.e. with breakdown)

.

5.2.2 Design Summary and Execution

The design selected was an eight factor, mixed level (either 2 or 3 levels), full factorial design, which required 1152 combinations. All these models were coded in separate program files to produce the output data for subsequent statistical analysis. Because the simulation model has many random variables, each model was run at ten times independently. Each replication covers 8-hours (480-minutes) of operation. The simulation model collected output statistics on the multiple replications and generated a multiple replication report for each run. The multiple replication report produced mean values for the performance variables for all replications. Mean values of the performance measures were then used to plot graphs to examine the relation between the factors and the performance measures. A sample graph is given in Figure 5.1, which shows the variation of truck productions in truck loads and the utilization of truck and shovels for different dispatching rules. The simulation results were then analyzed using ANOVA method.



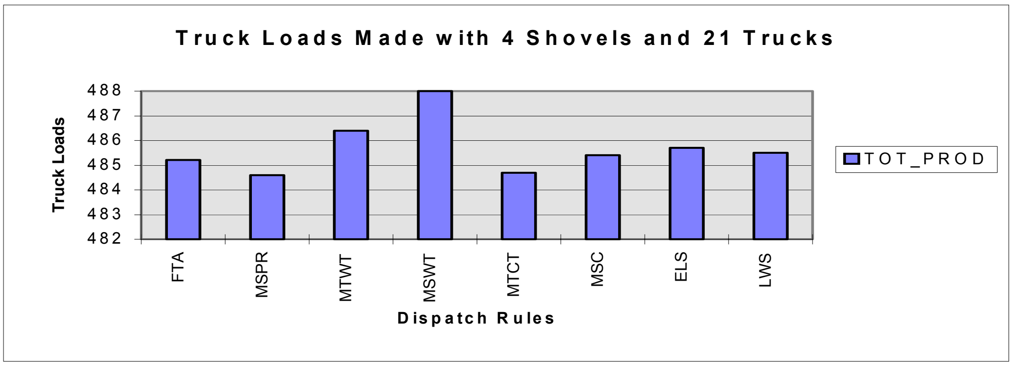


Figure 5.1 Relationship Between Performance Measures and the Dispatching Rules

5.2.3 Results

The full-factorial experimental design selected in this study resulted in 1152 simulation models and each simulation model was run independently with 10 replications to produce an estimate for the response variables. This resulted in 11520 runs. The output data from the simulation runs were then transferred to a single spreadsheet file in Minitab software manually to perform the statistical analysis using ANOVA method. Analysis of variance (ANOVA) procedures are often used to evaluate the results obtained from experimental designs and to test whether the individual factors or two factor interactions have any influence on the performance measures. Each response variable selected in this study was analyzed separately. The level of significance (α-value) is selected as 0.05. Those factors having p-values greater than the α-value of 0.05 are considered to be insignificant in ANOVA analysis. The p-value is defined as the smallest level of significance that could lead to rejection of the null hypothesis H_o. Tables 5.1, 5.2 and 5.3 show the ANOVA results for shovel utilization, truck utilization and truck productions, respectively. The ANOVA analysis was then carried out until all the factors having p-values greater than the critical α-value of 0.05 were neglected from the regression models. Tables 5.4, 5.5 and 5.6 summarize the results after performing this elimination process. It can be observed from Table 5.1 that the R^2 value is very low as 57.8 % for shovel utilization. However, it can be seen from Tables 5.2 and 5.3 that the R^2 values are satisfactory for the truck utilization and truck productions as 84.1 % and 79.6 %, respectively. From the tables, it can be seen that the dispatching rules do not affect the three performance measures significantly.

Table 5.1 ANOVA Results for Shovel Utilization, SU (%)

Predictor	Coef	SE Coef	T	P
Constant	-99.781	3.615	-27.60	0.000
DR	-0.06042	0.03118	-1.94	0.053
S	48.841	1.654	29.52	0.000
NT	4.5459	0.1458	31.18	0.000
SDD	142.348	4.906	29.02	0.000
LT	0.0826	0.1429	0.58	0.563
HT	-0.8900	0.1429	-6.23	0.000
RT	-0.5752	0.1429	-4.03	0.000
S*NT	-1.65068	0.03572	-46.21	0.000
S*SDD	-54.899	1.993	-27.54	0.000
S*NT*SDD	1.10942	0.05051	21.96	0.000
AV	-10.245	1.361	-7.53	0.000
AV*S	6.8301	0.7971	8.57	0.000
AV*NT	-1.1384	0.1391	-8.18	0.000
AV*SDD	5.506	2.195	2.51	0.012
AV*NT*SDD	-1.0118	0.3360	-3.01	0.003
AV*S*NT*SDD	0.02312	0.05051	0.46	0.647

S = 10.84 R-Sq = 57.8% R-Sq (adj) = 57.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	16	3713200	232075	1973.86	0.000
Residual Error	23023	2706914	118		
Total	23039	6420114			

Table 5.2 ANOVA Results for Truck Utilization, TU (%)

Predictor	Coef	SE Coef	T	P
Constant	5.422	1.642	3.30	0.001
DR	-0.16773	0.01416	-11.84	0.000
S	50.1431	0.7515	66.73	0.000
NT	-2.60221	0.06624	-39.28	0.000
SDD	117.726	2.229	52.83	0.000
LT	-0.34258	0.06490	-5.28	0.000
HT	-0.04391	0.06490	-0.68	0.499
RT	0.28674	0.06490	4.42	0.000
S*NT	-1.30140	0.01623	-80.21	0.000
S*SDD	-51.8906	0.9055	-57.31	0.000
S*NT*SDD	1.51119	0.02295	65.86	0.000
AV	-7.2326	0.6184	-11.70	0.000
AV*S	4.8217	0.3621	13.32	0.000
AV*NT	-0.80362	0.06319	-12.72	0.000
AV*SDD	-44.7095	0.9971	-44.84	0.000
AV*NT*SDD	3.4906	0.1526	22.87	0.000
AV*S*NT*SDD	-0.30243	0.02295	-13.18	0.000

S = 4.926 R-Sq = 84.2% R-Sq (adj) = 84.1%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	16	2967607	185475	7644.14	0.000
Residual Error	23023	558624	24		
Total	23039	3526232			

Table 5.3 ANOVA Results for Truck Production, TP (truckloads)

Predictor	Coef	SE Coef	T	P
Constant	-895.59	13.50	-66.36	0.000
DR	-0.3907	0.1164	-3.36	0.001
S	467.012	6.176	75.61	0.000
NT	15.4924	0.5444	28.46	0.000
SDD	1074.31	18.32	58.65	0.000
LT	-0.0826	0.5334	-0.15	0.877
HT	-2.6240	0.5334	-4.92	0.000
RT	-1.1220	0.5334	-2.10	0.035
S*NT	-12.1461	0.1334	-91.08	0.000
S*SDD	-478.408	7.442	-64.29	0.000
S*NT*SDD	12.6598	0.1886	67.13	0.000
AV	37.499	5.082	7.38	0.000
AV*S	-24.999	2.976	-8.40	0.000
AV*NT	4.1666	0.5193	8.02	0.000
AV*SDD	225.203	8.195	27.48	0.000
AV*NT*SDD	-25.765	1.255	-20.54	0.000
AV*S*NT*SDD	1.6829	0.1886	8.92	0.000

S = 40.48 R-Sq = 79.6% R-Sq(adj) = 79.6%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	16	147053513	9190845	5607.70	0.000
Residual Error	23023	37734004	1639		
Total	23039	184787517			

Table 5.4 Revised ANOVA Results for Shovel Utilization, (%)

Predictor	Coef	SE Coef	T	P
Constant	-100.859	3.680	-27.41	0.000
S	49.234	1.570	31.36	0.000
NT	4.5305	0.1336	33.90	0.000
SDD	143.833	4.271	33.68	0.000
HT	-0.8900	0.1428	-6.23	0.000
RT	-0.5752	0.1428	-4.03	0.000
S*NT	-1.65839	0.04124	-40.22	0.000
S*SDD	-55.350	1.732	-31.95	0.000
S*NT*SDD	1.12098	0.04374	25.63	0.000
AV	-17.284	2.558	-6.76	0.000
AV*S	12.1150	0.7107	17.05	0.000
AV*NT	-2.1193	0.1700	-12.47	0.000
AV*SDD	12.455	1.746	7.13	0.000
AV*S*SDD	-5.1693	0.4285	-12.06	0.000

S = 10.84 R-Sq = 57.9% R-Sq (adj) = 57.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	16	3714070	232129	1974.95	0.000
Residual Error	23023	2706045	118		
Total	23039	6420114			

Table 5.5 Revised ANOVA Results for Truck Utilization, (%)

Predictor	Coef	SE Coef	T	P
Constant	15.410	1.672	9.21	0.000
S	45.0017	0.7118	63.22	0.000
NT	-2.40059	0.06059	-39.62	0.000
SDD	104.940	1.938	54.15	0.000
LT	-0.34258	0.06477	-5.29	0.000
RT	0.28674	0.06477	4.43	0.000
S*NT	-1.20059	0.01870	-64.21	0.000
S*SDD	-45.9932	0.7856	-58.55	0.000
S*NT*SDD	1.35997	0.01983	68.57	0.000
AV	2.836	1.162	2.44	0.015
AV*S	-5.8391	0.3222	-18.12	0.000
AV*NT	2.28372	0.07710	29.62	0.000
AV*SDD	-47.8977	0.7916	-60.51	0.000
AV*S*SDD	9.1486	0.1943	47.08	0.000

S = 4.916   R-Sq = 84.2%   R-Sq(adj) = 84.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	17	2969855	174697	7228.71	0.000
Residual Error	23022	556376	24		
Total	23039	3526232			

Table 5.6 Revised ANOVA Results for Truck Production, (truckloads)

Predictor	Coef	SE Coef	T	P
Constant	-904.39	13.59	-66.52	0.000
S	467.012	6.170	75.69	0.000
NT	15.7598	0.5543	28.43	0.000
SDD	1079.22	18.33	58.88	0.000
HT	-2.6240	0.5329	-4.92	0.000
RT	-1.1220	0.5329	-2.11	0.035
S*NT	-12.1461	0.1332	-91.17	0.000
S*SDD	-478.408	7.434	-64.35	0.000
S*NT*SDD	12.6598	0.1884	67.19	0.000
AV	-189.814	7.951	-23.87	0.000
AV*S	129.589	4.706	27.53	0.000
AV*NT	-21.5981	0.7692	-28.08	0.000
AV*SDD	457.09	19.21	23.79	0.000
AV*S*SDD	-154.588	7.520	-20.56	0.000

S = 40.44   R-Sq = 79.6%   R-Sq (adj) = 79.6%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	18	147130988	8173944	4997.07	0.000
Residual Error	23021	37656529	1636		
Total	23039	184787517			

5.3 Adaptive Rule

An adaptive rule was developed to study its effect on the performance measures at the following conditions:

- The difference between the shovel utilization and truck utilization is to be minimized.
- Three basic dispatching rules that have the best performances were selected by carrying out Tukey's mean comparison test.

Multiple comparison methods are applied to compare the treatment means. Tukey's method is selected in this study to compare the mean performance measures. Tukey's method gives confidence intervals for the difference between means performance measure. The mean differences which do not include zero are considered to be significant. Tables 5.7, 5.8, and 5.9 show the results for Tukey's test for shovel utilization, truck utilization and truck production, respectively. When Tables 5.8 and Table 5.9 are compared to each other, it can be seen that both truck utilization and truck production are affected in the same manner by the same dispatch rules. Therefore, only shovel utilization and truck utilization performances were considered in developing the adaptive rule.

Table.5.7 Results for Tukey’s Mean Comparison Test for Shovel Utilization, (%)

```
                                  Individual 95% CIs for Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev -------+---------+---------+---------
1        1440     51,74     16,82                  (-----*-----)
2        1440     49,85     16,82      (----*-----)
3        1440     51,65     16,18                  (----*-----)
4        1440     51,54     16,56                 (-----*----)
5        1440     51,89     15,95                   (-----*-----)
6        1440     49,63     16,67    (-----*-----)
7        1440     52,20     15,86                     (-----*-----)
8        1440     49,35     16,27  (-----*-----)
                                   -------+---------+---------+---------
Pooled StDev =    16,40                    49,5      51,0      52,5

Tukey's pairwise comparisons

    Family error rate = 0,0500
Individual error rate = 0,00242

Critical value = 4,29
```

Table.5.8 Results for Tukey’s Mean Comparison Test for Truck Utilization, (%)

```
                                 Individual 95% CIs for Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev  ----+---------+---------+---------+--
1        1440     81,74     10,78                      (----*----)
2        1440     79,53     12,46    (----*----)
3        1440     81,57     11,75                     (----*----)
4        1440     82,22     11,40                          (----*----)
5        1440     81,15     11,80                 (----*----)
6        1440     79,89     12,15       (----*----)
7        1440     79,45     12,32   (----*----)
8        1440     79,55     12,49    (----*----)
                                   ----+---------+---------+---------+--
Pooled StDev =    11,91             79,2      80,4      81,6      82,8

Tukey's pairwise comparisons

    Family error rate = 0,0500
Individual error rate = 0,00242

Critical value = 4,29
```

Table 5.9 Results for Tukey's Mean Comparison Test for Truck Production, (truckloads)

```
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
1        1440    383,67     92,95                    (----*---)
2        1440    369,31     93,66      (---*----)
3        1440    382,96     86,88                   (----*----)
4        1440    382,26     91,42                   (---*----)
5        1440    385,38     86,83                      (---*----)
6        1440    367,67     93,26    (----*---)
7        1440    387,50     84,95                        (----*---)
8        1440    366,00     92,51  (----*----)
                                   ---------+---------+---------+-------
Pooled StDev =    90,37                  370       380       390

Tukey's pairwise comparisons

    Family error rate = 0,0500
Individual error rate = 0,00242

Critical value = 4,29
```

The following three basic dispatching rules which provided the best performances both for shovel utilization and truck utilization under most of the conditions considered in this study were accepted in developing the adaptive rule.

1) Minimizing Shovel Coverage (MSC)
2) Minimizing Shovel Waiting Time (MSWT)
3) Earliest Loading Shovel (ELS)

5.4 Experiment 2

The adaptive rule developed was numbered as level 9 and all the levels of dispatching rules were tested by ANOVA method again to compare the performance of the adaptive rule with the other basic rules. The full-factorial experimental design selected in this study resulted in 2592 simulation models and each simulation model was run with 10 replications to produce an estimate for the response variables. This resulted in 25920 runs. The design of simulation experiment for Experiment 2 is given in Table 5.10 below.

The results of simulation experiments for Experiment 2 are given below. Table 5.11, 5.12, and 5.13 shows the ANOVA results for all basic dispatching rules including the adaptive rule.

Table 5.10 Design Summary for Experiment 2

FACTORS	NUMBER OF LEVELS	TREATMENTS
Dispatching rules, DR	9	1. Fixed Truck Assignment, (FTA) 2. Minimizing Shovel Production Requirements, (MSPR) 3. Minimizing Truck Waiting Time, (MTWT) 4. Minimizing Shovel Waiting Time, (MSWT) 5. Minimizing Truck Cycle Time, (MTCT) 6. Minimizing Shovel Coverage, (MSC) 7. Earliest Loading Shovel (ELS) 8. Longest Waiting Shovel (LWS) 9. Adaptive Rule (AR)
Number of Trucks, NT	3	9, 15, and 21
Number of Shovels, S	3	3,4, and 5
Truck Loading Time, LT	2	N(2.5,0.25) and N(2.5,0.50)
Truck Hauling Time, HT	2	N(5.5,0.50) and N(5.5,1.0)
Truck Return Time, RT	2	N(4.5,0.4), and N(4.5,0.8)
Distance Between Shovels and Dumpsite, SDD	2	-All shovels at the same distance and 1-minute difference in means for all shovels
Availability of Shovels and Trucks, AV	2	- Without breakdowns for all shovels and trucks or - With exponential breakdowns (i.e. Exp(45), Exp(40), Exp(5), and Exp(10))

Table 5.11 ANOVA Results for Shovel Utilization, SU (%), With All Dispatching Rules

Predictor	Coef	SE Coef	T	P
Constant	14,855	1,190	12,48	0,000
DR	-0,20632	0,08035	-2,57	0,010
S	0,8770	0,4165	2,11	0,035
NT	4,50612	0,07702	58,51	0,000
SDD	31,477	1,349	23,33	0,000
LT	0,0707	0,1163	0,61	0,543
HT	-0,8097	0,1163	-6,96	0,000
RT	-0,4046	0,1163	-3,48	0,001
AV	25,6283	0,9746	26,30	0,000
S*NT	-0,43823	0,01586	-27,62	0,000
S*SDD	-5,2863	0,4948	-10,68	0,000
S*NT*SDD	-0,20020	0,01329	-15,06	0,000
AV*S	-5,2866	0,3324	-15,90	0,000
AV*NT	-0,95545	0,05398	-17,70	0,000
AV*SDD	-49,112	1,565	-31,38	0,000
AV*S*SDD	13,5090	0,5446	24,81	0,000
AV*S*NT*SDD	-0,12207	0,01535	-7,95	0,000
DR*AV	0,01683	0,04509	0,37	0,709
DR*NT	0,008508	0,004672	1,82	0,069
DR*SDD	0,02431	0,04509	0,54	0,590

S = 9,361   R-Sq = 65,4%   R-Sq(adj) = 65,4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	19	4294987	226052	2579,91	0,000
Residual Error	25900	2269357	88		
Total	25919	6564345			

Table 5.12 ANOVA Results for Truck Utilization, TU (%), With All Dispatching Rules

Predictor	Coef	SE Coef	T	P
Constant	105,967	0,738	143,58	0,000
DR	0,16294	0,04983	3,27	0,001
S	4,4827	0,2583	17,35	0,000
NT	-1,48423	0,04777	-31,07	0,000
SDD	-1,6871	0,8368	-2,02	0,044
LT	-0,32780	0,07212	-4,55	0,000
HT	-0,07558	0,07212	-1,05	0,295
RT	0,24063	0,07212	3,34	0,001
AV	-25,1819	0,6044	-41,66	0,000
S*NT	-0,286222	0,009839	-29,09	0,000
S*SDD	-0,3075	0,3069	-1,00	0,316
S*NT*SDD	0,024993	0,008242	3,03	0,002
AV*S	1,5035	0,2062	7,29	0,000
AV*NT	0,63593	0,03348	18,99	0,000
AV*SDD	6,4272	0,9706	6,62	0,000
AV*S*SDD	-5,6373	0,3378	-16,69	0,000
AV*S*NT*SDD	0,376404	0,009517	39,55	0,000
DR*AV	-0,21707	0,02796	-7,76	0,000
DR*NT	-0,017704	0,002897	-6,11	0,000
DR*SDD	0,08001	0,02796	2,86	0,004

S = 5,805 R-Sq = 79,4% R-Sq(adj) = 79,4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	19	3369003	177316	5261,39	0,000
Residual Error	25900	872864	34		
Total	25919	4241867			

Table 5.13 ANOVA Results for Truck Productions, TP (truckloads), and With All Dispatching Rules

Predictor	Coef	SE Coef	T	P
Constant	196,275	6,171	31,81	0,000
DR	-2,6368	0,4166	-6,33	0,000
S	11,765	2,160	5,45	0,000
NT	12,4969	0,3994	31,29	0,000
SDD	21,307	6,996	3,05	0,002
LT	-0,1731	0,6030	-0,29	0,774
HT	-2,4645	0,6030	-4,09	0,000
RT	-0,1667	0,6030	-0,28	0,782
AV	-67,316	5,053	-13,32	0,000
S*NT	-0,11943	0,08226	-1,45	0,147
S*SDD	-10,198	2,566	-3,97	0,000
S*NT*SDD	0,34739	0,06891	5,04	0,000
AV*S	1,876	1,724	1,09	0,276
AV*NT	0,2574	0,2799	0,92	0,358
AV*SDD	12,476	8,115	1,54	0,124
AV*S*SDD	26,436	2,824	9,36	0,000
AV*S*NT*SDD	-2,49010	0,07957	-31,30	0,000
DR*AV	-0,7497	0,2338	-3,21	0,001
DR*NT	0,20719	0,02422	8,55	0,000
DR*SDD	-0,3565	0,2338	-1,53	0,127

S = 48,54 R-Sq = 69,3% R-Sq(adj) = 69,3%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	19	137732860	7249098	3077,11	0,000
Residual Error	25900	61015606	2356		
Total	25919	198748466			

Table 5.14, 5.15, and 5.16 shows the ANOVA results for the revised case including the adaptive rule after elimination process.

Table 5.14 Revised ANOVA Results for Shovel Utilization, (%)

Predictor	Coef	SE Coef	T	P
Constant	31,073	1,043	29,79	0,000
S	-7,1694	0,3347	-21,42	0,000
NT	5,36801	0,06927	77,49	0,000
SDD	-3,3049	0,7076	-4,67	0,000
S*NT	-0,39041	0,01606	-24,31	0,000
S*SDD	6,8597	0,2924	23,46	0,000
S*NT*SDD	-0,43484	0,01068	-40,72	0,000
AV*NT	-1,83610	0,03949	-46,49	0,000
AV*S	4,1553	0,1564	26,56	0,000
AV*S*SDD	-1,6978	0,2049	-8,29	0,000
DR*AV	0,12411	0,04193	2,96	0,003
DR*NT	-0,008190	0,001930	-4,24	0,000
AV*S*NT*	0,08929	0,01266	7,05	0,000

S = 9,556   R-Sq = 64,0%   R-Sq(adj) = 63,9%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	12	4198441	349870	3831,13	0,000
Residual Error	25907	2365903	91		
Total	25919	6564345			

Table 5.15 Revised ANOVA Results for Truck Utilization, (%)

Predictor	Coef	SE Coef	T	P
Constant	98,5550	0,6427	153,34	0,000
S	6,0405	0,1783	33,88	0,000
NT	-1,55558	0,04274	-36,40	0,000
SDD	1,0112	0,4032	2,51	0,012
S*NT	-0,27333	0,01001	-27,32	0,000
S*SDD	-0,4545	0,1012	-4,49	0,000
AV*NT	0,19248	0,01796	10,72	0,000
AV*S	-2,46775	0,07364	-33,51	0,000
AV*S*SDD	-5,72835	0,08284	-69,15	0,000
DR*AV	-0,58890	0,02665	-22,09	0,000
DR*NT	0,006242	0,001228	5,08	0,000
AV*S*NT*	0,483324	0,004999	96,68	0,000

S = 6,089   R-Sq = 77,4%   R-Sq(adj) = 77,3%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	11	3281241	298295	8044,98	0,000
Residual Error	25908	960626	37		
Total	25919	4241867			

Table 5.16 Revised ANOVA Results for Truck Production, (truckloads)

Predictor	Coef	SE Coef	T	P
Constant	194,650	2,178	89,39	0,000
S	4,2130	0,5842	7,21	0,000
NT	14,1766	0,0974	145,61	0,000
AV	-77,135	4,143	-18,62	0,000
AV*S	7,6370	0,9428	8,10	0,000
AV*NT	-0,8458	0,1553	-5,45	0,000
AV*SDD	32,000	4,273	7,49	0,000
AV*S*SDD	16,376	1,221	13,41	0,000
AV*S*NT*	-2,15189	0,04190	-51,36	0,000

S = 48,64   R-Sq = 69,2%   R-Sq(adj) = 69,1%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	8	137446144	17180768	7261,89	0,000
Residual Error	25911	61302322	2366		
Total	25919	198748466			

As it can be seen from above tables, R^2 values are 69.3 % for shovel utilization, 77.3 % for truck utilization and 69.1 % for total productions. Table 5.17, 5.18, and 5.19 shows the mean comparison test for the revised case including the adaptive rule using Tukey's method.

Table.5.17 Revised Results for Tukey's Mean Comparison Test for Shovel Utilization, (%)

```
Analysis of Variance for SU
Source     DF       SS       MS        F        P
DR          8    33074     4134    16,40    0,000
Error   25911  6531271      252
Total   25919  6564345
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N     Mean    StDev    -------+---------+---------+---------
1        2880    52,89    16,39                           (----*----)
2        2880    50,71    16,23         (----*---)
3        2880    52,35    15,88                     (----*----)
4        2880    52,67    16,07                        (----*----)
5        2880    52,74    15,57                         (----*---)
6        2880    50,54    16,19       (----*----)
7        2880    53,46    15,55                               (---*----)
8        2880    50,25    15,77     (----*----)
9        2880    52,78    15,21                         (----*----)
                                   -------+---------+---------+---------
Pooled StDev =    15,88                50,4      51,6      52,8

Tukey's pairwise comparisons

    Family error rate = 0,0500
Individual error rate = 0,00191

Critical value = 4,39
```

Table.5.18 Revised Results for Tukey's Mean Comparison Test for Truck Utilization, (%)

```
Analysis of Variance for TU
Source     DF        SS        MS        F        P
DR          8     29181      3648    22,44    0,000
Error   25911   4212686       163
Total   25919   4241867
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
1        2880     80,45     11,57                        (--*---)
2        2880     77,84     13,58   (---*---)
3        2880     80,36     12,58                       (---*---)
4        2880     80,92     12,24                           (---*---)
5        2880     79,89     12,59                   (---*---)
6        2880     78,38     13,21       (---*---)
7        2880     79,11     12,74             (---*---)
8        2880     77,98     13,49    (---*---)
9        2880     79,33     12,64               (---*---)
                                   ------+---------+---------+---------+
Pooled StDev =    12,75                78,0      79,2      80,4      81,6

Tukey's pairwise comparisons

    Family error rate = 0,0500
Individual error rate = 0,00191

Critical value = 4,39
```

Table.5.19 Revised Results for Tukey's Mean Comparison Test for Truck Productions, (truckloads)

```
Analysis of Variance for TP
Source     DF        SS        MS        F        P
DR          8   1961220    245152    32,28    0,000
Error   25911 196787246      7595
Total   25919 198748466
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -+---------+---------+---------+-----
1        2880    392,61     89,29                      (---*--)
2        2880    376,24     89,22      (--*--)
3        2880    388,57     84,64                  (---*--)
4        2880    391,12     87,50                     (--*--)
5        2880    392,12     84,13                      (--*--)
6        2880    374,85     88,84     (--*--)
7        2880    397,37     82,91                           (--*---)
8        2880    373,14     88,20   (--*--)
9        2880    393,49     89,30                       (--*---)
                                   -+---------+---------+---------+-----
Pooled StDev =    87,15           370       380       390       400

Tukey's pairwise comparisons

    Family error rate = 0,0500
Individual error rate = 0,00191

Critical value = 4,39
```

5.5 Result Summary

It can be observed from Table 5.1 that the R^2 value is very low as 57.8 % for shovel utilization. However, it can be seen from Tables 5.2 and 5.3 that the R^2 values are satisfactory for the truck utilization and truck productions as 84.1 % and 79.6 %, respectively. From the tables, it can be seen that the dispatching rules do not affect the three performance measures significantly. Also, the variability in all cycle times (i.e. truck loading times, truck hauling times, and truck return times) are all insignificant on the three performance measures. However, the main factors affecting all three performance measures are the number of trucks operating, the number of shovels operating, the distance between the shovels and dumping site, and the availability of shovel and truck resources. There are also significant interaction effects between some of the main factor such as number of trucks and number of shovels operating.

The ANOVA results with adaptive rule gives higher R^2 values compared to the ANOVA results with basic dispatching rules only for shovel utilization. However, the ANOVA results gives lower R^2 values with the adaptive rule compared to the ANOVA results with basic dispatching rules only for both the truck utilization and the truck productions.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

In this dissertation, computer simulation models were developed using GPSS/H software for a hypothetical medium-sized open pit mine consisting of several production faces and a single dump location. Truck dispatching systems were examined and it was found that they offered the potential for improving the performances of open pit haulage systems. Truck dispatching issue in open-pit mines took place in a dynamic environment with performance being a function of competing parameters. Stochastic simulation approach was considered as the most appropriate technique to assess the dispatching policies due to the variability of the interdependent components of truck/shovel operations. The simulation program developed was structured on the process-orientation approach of discrete-event simulation technique to enable the insertion of dispatching rules in a haulage network. The validation of computer models was done by the interactive debugging facility of the PROOF Animation Software. The real-time animation capability of the models enabled the modeler to visually observe the dynamic activities of the truck/shovel systems. In this study, eight basic heuristic dispatching policies were modeled to test the effects of dispatching rules. Also, an adaptive rule was developed using the standardized utilizations of shovel and trucks resources.

The dispatching algorithms based on heuristic rules provided the simplest approach to computer-based truck dispatching problem. They were also easier to implement and did not require much computations when making the dispatching decisions in real-time. Therefore, they could also be implemented in very large and complex mining operations. Heuristics-based dispatching could bring about improvement in production by reducing waiting times of equipment resources. The undertrucked or overtrucked status of the systems would play a critical role in determining the usefulness various heuristics. The benefits of dispatching would be more in the case of complex haulage networks due to the high interference between systems components.

Computer simulation experiments were made to investigate the effects of several decision factors likely to affect the performance of these systems. These factor were as follows: the dispatching rules applied, the number of trucks operating, the number of shovels operating, the variability in truck loading, hauling and return times, the distance between the shovels and the dump site, and the availability of shovel and truck resources. Three performance measures selected were the total truck productions (i.e. truckloads), overall shovel utilization, and overall truck utilization. Full factorial simulation experiments were performed to provide the necessary output data for subsequent statistical analysis. ANOVA analyses and Tukey's mean comparison tests were carried out on the simulation results. From the results of statistical analysis, it was concluded that the effect of basic dispatching rules on all of the selected performance measures were not so significant. Also, the effect of truck cycle time components (i.e. loading, hauling, and return) was not significant, either. However, the main factors affecting the three performances were the number of truck operating (i.e. undertrucked or overtrucked status of system), the number of shovels operating, the distance between the shovels and the dumping site, and the availability of shovel and truck resources. There were also significant interaction effects between these main factors. Finally, the following conclusions were made:

a) The dispatching criteria values should be calculated as a function of the present status of the system, thus there is no extra data requirement.
b) The existing heuristic rules were very weak in trying to simultaneously attain multiple performance goals such as productivity and utilization.
c) By their very nature, these rules would provide truck assignment to the shovels only in a one-truck-at-a-time. Hence, myopic decisions are made.
d) The current truck at the dispatching station was dispatched to the shovel where it contributed the most. However, the global optimal decision should consider all trucks all times that are expected to request dispatching decisions in the near future.
e) Each mine was very unique and, therefore, should evaluate each policy separately according to its objectives. Implementing a truck dispatching system with a specific dispatching policy could not ensure the desired benefits for all situations.
f) The development of reasonably inexpensive and powerful computer resources together with the increasing programming abilities of software developers would allow a wide choice of dispatching systems to become commercially viable for medium-sized open-pit mines, also.

g) The simulation results confirmed conclusions made by previous researchers such that no basic rule dominates all others under all conditions.

h) The adaptive rule developed improves the system's performances slightly under most of the cases studied.

The following directions are addressed for further research.

- The simulation model developed in this study can be modified to consider the case of variable number of operating shovels to prompt the users for entering the number of shovels as an input parameter. Also, the simulation experiments can be extended to include a wider range of operating number of trucks to determine the optimum conditions based on numerical results.
- More dispatching rules could be developed and statistically compared with the existing nine rules.
- Low R^2 values indicated the need for searching other factors affecting the performances of open-pit mining systems such as non-identical distributions for truck cycle time components.
- The simulation model developed should be validated in an existing real open-pit mine system.
- Analytical stochastic models for the open-pit haulage systems like queuing networks could be developed. These models can be verified by the

simulation results. Finally, some system parameters could be optimized using the analytical models.

- Data warehouses could be developed for real systems in which the production related data are stored. These data could be analyzed using data mining techniques to assist the decision makers in increasing the productivity as well as utilizations.
- The basic assumptions of single dispatching point, single truck type, single shovel type, single material destination can be relaxed and studied for a complex mine.

REFERENCES

Ataeepour, M., and Baafi, E., 1999. "ARENA Simulation Model for Truck-Shovel Operation in Dispatching and Non-Dispatching Modes ", Int. Journal of Surface Mining, Reclamation and Environment, Vol. 13, pp. 125-129

Banks, L., and Carson, J., 1996. Discrete-Event System Simulation, Prentice Hall Inc.

Billette, N. R., and Seka, B.P., 1986. "Haulage system Capacity: analytical and Simulation Models Revisited", 19th APCOM, AIME, Littleton, Colorado, pp. 377-396.

Bonates, E., 1993. "The Development of Assignment Procedures for Truck Dispatching", Mine Mechanization and Automation, Almgren, Kumar and Vegenas (Eds), Balkema, Rotterdam, pp. 534-553.

Bonates, E., and Lizotte, Y., 1987. "A Computer Simulation Model to Evaluate the Effect of Dispatching", Preprint 87-17, SME AIME Annual Meeting, Phoenix, Arizona.

Brake, J. D., and Chatterjee, K. P., 1979. "Evaluation of Truck Dispatching and Simulation Methods in Large-Scale Open Pit Operations", 16th APCOM, AIME, pp. 375-381.

Cross, B. K., and Williamson, G. B., 1969. "Digital Simulation of an Open Pit Truck Haulage System", A Decade of Digital Computing in the Mineral Industry, Weiss, A., (Ed), AIME, New York, pp. 385-400.

Forsman, B., and Vegenas, N., 1992." Using METAFORA to Evaluate the Transport System In a Swedish Open Pit Mine", 23rd APCOM, SME, pp. 733-738.

Hauck, R. F., 1979. "Computer-Controlled Truck Dispatching in Open-Pit Mines", Computer Methods for the 80's in the Mineral Industry, AIME, New York, pp. 735-742.

Hagenbuch, L., 1988. "The Basic Factors Involved and Putting These Factors into Mathematical formulas (Algorithms)", Int. Journal of Surface Mining, Vol. 1, No. 2, pp. 105-129.

Himebaugh, A. E., 1980. "Computer-Based Truck Dispatching in the Tyrone Mine", Mining Congress Journal, Vol. 66, No. 11, November, pp. 16-21.

Hodson, D. I., and Barker, K. S., 1985. "The Design and Development of a Computerized Truck Dispatching System", Mining Conference, Birmingham, UK, June, 83-90.

Kennedy, B. A., 1990. Surface Mining, 2nd Ed, SME, Littleton, Colorado.

Kim, Y. C., and Ibarra, M. A., 1981. "Truck Dispatching by Computer Simulation", Bulk Solids Handling, Vol. 1, No. 1, pp. 137-147.

Kolonja, B., 1992. "Simulation Analysis of Dispatching Strategies for Surface Mining Operations Using SIMAN", M. Sc. Thesis, Pennsylvania State University.

Kolonja, B., and Mutmansky, J. M., 1993. "Analysis of Truck Dispatching Strategies for Surface Mining Operations Using SIMAN", SME Preprint 93-177, SME Annual Meeting, Reno, NV.

Kolonja, B., and Vasiljevic, N., 2000. "Computer Simulation of Open-Pit Transportation Systems", Mine Planning and Equipment Selection, Panagiotou and Michalakopoulos (Eds), Balkema, Rotterdam, pp. 613-618.

Law, A., Kelton, W., 1996. Simulation Modeling and Analysis, McGraw-Hill, Inc., New York, NY.

Li, Z., 1990. "A Methodology for the Optimum Control of Shovel and Truck Operations in Open-Pit Mining", Mining Science and Technology, Vol. 10, pp. 337-340.

Lizotte, Y., and Bonates, E., 1987. "Truck and Shovel Dispatching Rules Assessment Using Simulation", Mining Science and Technology, Vol. 5, pp. 45-58.

Mueller, E. R., 1977. “Simplified Dispatching Board Boosts Truck Productivity at Cyprus Pima", Vol. 29, No. 8, Mining Engineering, August, pp. 40-43.

Munirathinam, M. and Yingling, J. C., 1994. "A Review of Computer-Based Truck Dispatching Strategies for Surface Mining Operations", Int. Journal of Surface Mining, Reclamation and environment, Vol. 8, pp. 1-15.

Nenonen, L. K., 1982. "Interactive Computer Modeling of Truck Haulage Systems", CIM Bulletin, Vol. 75, No. 847, November, pp. 84-89.

Sadler, W. M., 1988. “Practical Truck Dispatch- A Micro Computer Based Approach", Computer App. In Mineral Industry, Fytas, Collins and Singhal (Eds), pp. 495-500.

Soumis, F., Ethier, J., and Elbrond, J., 1989. "Truck Dispatching in an Open-Pit Mine", Int. Journal of surface Mining, Vol. 3, pp. 115-119.

Sturgul, J. R., 1987. "Simulation Models to Study the Effect of Computerized Truck Dispatching in a Mine", Engineering and Mining Journal, Vol. 188, No. 4, pp. 70-72.

Szymanski, J. K., Srajer, V., and Kempe, A., 1989. "An Integrated Monitoring System and Simulation Analysis Model for Trucks Operation Using SLAM II", Off-Highway Haulage in Surface Mines, Golosinski and Srajer (Eds), Balkema, Rotterdam, pp. 75-81.

Tan, S., 1992. "Production Planning and Operational Control; New Algorithms with Application to the Mining Industry", Ph.D. Thesis, the Pennsylvania State University.

Tan, S., and Ramani, R. V., 1992. “Evaluation of Computer Truck Dispatching Criteria", Preprint 92-215, SME AIME Annual Meeting, Phoenix, Arizona.

Temeng, V. A., Francis, O. O., and James, O. F., 1997. "Real-Time Truck Dispatching Using A Transportation Algorithm", Int. Journal of Surface Mining, Vol. 11, pp. 203-207.

Tu, H. J., and Hucka, V. J., 1985. "Analysis of Open Pit Truck Haulage System by Use of a Computer Model", CIM Bulletin, Vol. 78, No. 879, July, pp. 63-59.

White, J. W., and Olson, J. P., 1992. "On Improving Truck/Shovel Productivity in Open-Pit Mines", 23rd APCOM, SME, pp. 739-746.

Wilke, F. L., and Heck, K., 1982. "Simulation Studies on Truck Dispatching", 17th APCOM, AIME, New York, pp. 620-626.

Xi, Y., and Yegulalp, T. M., 1994. "Optimum Dispatching Algorithms for Anshan Open-Pit Mine", 24th APCOM Proceedings, pp. 426-433.

Youdi, Z., Jing, S., Shuguang, L., and Daxian, Z., 1994. "System Simulation of Optimal Truck Dispatching Criteria in open Cut Mining", Mine Planning and Equipment Selection, Pasamehmetoglu, et al. (Ed), Balkema, Rotterdam, pp. 307-311.

Zhang, Y., Li, S., and Cai, Q., 1990."Optimization Criteria for Computer-Controlled Truck Dispatching Systems", 22nd APCOM, Berlin, Germany, pp. 297-306.

APPENDIX

Program Code for Minimizing Shovel Production Requirement

(MSPR) Rule

```
**************************************************************
*
*      Filename:  MSPR.GPS        Date: 10.02.2003
*
*      Programmed By: Necmettin CETIN
*
*      A Three-Shovels Operating at a Single Material Type With
*
*      Heuristic Truck Dispatching Done By
*
*      Minimizing Shovel Production Requirements (MSPR) Rule
*
*      Truck Loading Time with Low Variance   (0.25)
*
*      Truck Hauling Time with Low Variance   (0.50)
 *
*      Truck Returning Time with High Variance    (0.8)
*
***************************************************************

      SIMULATE

      REALLOCATE   COM, 400000

OUT1    FILEDEF     'MSPR35.OUT'
OUT2    FILEDEF     'MSPR3123.OUT'
OUT3    FILEDEF     'MSPR3125.OUT'
OUT4    FILEDEF     'MSPR3127.OUT'
*
*      Global Variable Declarations
*
 INTEGER     &TSHIFT                      Duration of shift time

 INTEGER     &I                     Index for Replication Number

  INTEGER     &DISPTCH                    Integer Global Variable to be used
*                                          For New Truck Assignments,
*
```

```
*                              $$$ ONE TRUCK DISPATCHED AT ANY TIME
$$$

*
 INTEGER     &TRUCKID              Integer Global Variable to be used
*                                       For truck ID's

  INTEGER     &NUMTK
  REAL        &TOTL,&TOWAIT
  REAL        &TOT1,&TOT2,&TOT3,&TOT4
  REAL        &TOT5,&TOT6,&TOT7

  REAL        &AVE1,&AVE2,&AVE3,&AVE4
 REAL        &AVE5,&AVE6,&AVE7,&UTIL
 REAL        &AVSUTIL

 REAL        &TOTWAIT(4)

 REAL        &PAY1(10),&PAY2(10),&PAY3(10),&TPAY(10)
 REAL        &SWAIT1(10),&SWAIT2(10),&SWAIT3(10)
 REAL        &DWAIT(10),&TUTIL(10)
 REAL        &TWAIT1(10),&TWAIT2(10),&TWAIT3(10)
 REAL        &TWAITD(10),&TTWAIT(10)

 REAL        &TLOAD(10)
 REAL        &SUTIL(10)

 REAL        &WASTETON             Global Variable for Total Tons Dumped

  REAL        &TARGET(3)            Shovel production targets

  REAL        &PRODTOT(3)            Total Shovel Productions to be
*                                       Made at Current Simulation Time

 REAL        &PRODNOW(3)           Total Number of Truck Assignments
*                                       Made at Current Simulation Time

 REAL        &PAYLOAD(3)           Total Number of Trucks Assigned to
*                                      Each Shovels, But Not Loaded Yet

 REAL        &DSPCH(3)                 Array Global Variables to be Used
*                                      To Calculate Truck's Loads Ratios

 REAL        &TOTAL(3)                 Total Truck Loads Made Until Now

  INTEGER     &NUMTRK(3)             Number of Trucks Initially Assigned
```

```
 REAL       &RETURN(3)              Global Variable for truck return time

 REAL       &HAUL(3)                Global Variable for truck haul time

 REAL       &LOAD(3)                Global Variable for truck loading time

 STORAGE    S(DUMP),1               One Truck Can Dump Their Loads
*                                        At Dumping Area
*

*      Initialize Model Input Parameters
*
 LET        &TARGET (1) =145        Set Shovel 1 Production Target
*                                      To 145 Truck Loads

 LET        &TARGET (2) =145        Set Shovel 2 Production Target
*                                      To 145 Truck Loads

 LET        &TARGET (3) =145        Set Shovel 3 Production Target
*                                      To 145 Truck Loads

 PUTSTRING  'ENTER THE NUMBER OF TRUCKS FOR NORTH PHASE

                 PIT:'

GETLIST     &NUMTRK(1)

 PUTSTRING  'ENTER THE NUMBER OF TRUCKS FOR SOUTH PHASE
PIT:'

 GETLIST    &NUMTRK(2)

 PUTSTRING  'ENTER THE NUMBER OF TRUCKS FOR EAST PHASE PIT:'

GETLIST     &NUMTRK(3)

 LET        &TSHIFT=480                 Set Shift Duration to 480 Minutes

 LET        &PRODTOT(1)=0           Initialize &PRODTOT(1) to Zero

 LET        &PRODTOT(2)=0           Initialize &PRODTOT(2) to Zero

 LET        &PRODTOT(3)=0           Initialize &PRODTOT(3) to Zero

 LET        &PRODNOW(1)=0           Initialize &PRODNOW(1) to Zero

 LET        &PRODNOW(2)=0           Initialize &PRODNOW(2) to Zero
```

```
 LET        &PRODNOW(3)=0          Initialize &PRODNOW(3) to Zero

 LET        &PAYLOAD(1)=&NUMTRK(1)    Initialize &PAYLOAD(1) to
                                       NUMTRK(1)

LET        &PAYLOAD(2)=&NUMTRK(2)    Initialize &PAYLOAD(2) to
                                      &NUMTRK(2)

LET        &PAYLOAD(3)=&NUMTRK(3)    Initialize &PAYLOAD(3) to
                                      &NUMTRK(3)

LET        &TOTAL(1)=0            Initialize Shovel 1 Loads to Zero

LET        &TOTAL(2)=0            Initialize Shovel 2 Loads to Zero

 LET        &TOTAL(3)=0            Initialize Shovel 3 Loads to Zero

 LET        &WASTETON=0            Initialize Total Waste Tons
*                                   Dumped to Zero
*
*
*    GPSS/H Block Section
*

GENERATE    ,,,1                   Create a Shovel Transaction
                                    for North Pit (Shovel 1)
 ASSIGN      1,10,PH

NEXT1   QUEUE       SHOVEL1            Start SHOVEL1 Queue
                                        Membership

 TEST G      W(BACK1),0                Is There Any Trucks-XACT's
                                        Waiting in Shovel 1 Queue ?

 DEPART      SHOVEL1                   End SHOVEL1 Membership

  SEIZE       SHOVEL1                  Capture Shovel 1 Resource

  LOGIC S     SPOT1                    Shovel 1 Signals to Truck to Spot

   BUFFER                              Shovel 1 XACT Buffers to
*                                       Let Truck-XACT Start to Spot

  BLET        &LOAD(1)=RVNORM(1,2.5,0.25)

  ADVANCE     &LOAD(1)                  Truck Loading Time at Shovel 1
```

```
 LOGIC S     LEAVE1                    Shovel 1 Signals to Truck to Leave

RELEASE     SHOVEL1                    Free Shovel 1 Resource

BLET        &TOTAL(1)=&TOTAL(1)+1        Update Total Loads Made by
                                         Shovel 1

 BLET        &PAYLOAD(1)=&PAYLOAD(1)-1       Update Number of Truck
                                         Payloads Already Assigned to Shovel
1,                                       But, Not Loaded Yet

 BUFFER                          Shovel 1 XACT Buffers to
*                               Let Truck-XACT Start to Haul

TRANSFER    ,NEXT1                     Shovel 1 Returns Back to Load

*                                      Next Truck in Shovel 1 Queue
*
*************************************************************
*
GENERATE     ,,,1                 Create a Shovel Transaction
*                                 for South Pit (Shovel 2)
*
ASSIGN      1,20,PH

NEXT2   QUEUE      SHOVEL2                  Start SHOVEL2 Queue
                                               Membership

TEST G      W(BACK2),0               Is There Any Trucks-XACT's
                                 Waiting in Shovel 2 Queue ?

DEPART      SHOVEL2                  End SHOVEL2 Membership

 SEIZE      SHOVEL2                  Capture Shovel 2 Resource

  LOGIC S     SPOT2                  Shovel 2 Signals to Truck to Spot

  BUFFER                          Shovel 2 XACT Buffers to
*                                 Let Truck-XACT Start to Spot

  BLET       &LOAD(2)=RVNORM(1,2.5,0.25)

  ADVANCE     &LOAD(2)                  Truck Loading Time at Shovel 2

   LOGIC S     LEAVE2                  Shovel 2 Signals to Truck to Leave
```

```
  RELEASE     SHOVEL2                 Free Shovel 2 Resource

  BLET       &TOTAL(2)=&TOTAL(2)+1        Update Total Loads Made by
                                           Shovel 2

  BLET       &PAYLOAD(2)=&PAYLOAD(2)-1     Update Number of Truck
                                           Payloads Already Assigned to
                                            Shovel 2, But, Not Loaded
  Yet

  BUFFER                          Shovel 2 XACT Buffers to
*                                 Let Truck-XACT Start to Haul

  TRANSFER    ,NEXT2                  Shovel 2 Returns Back to Load
*                                        Next Truck in Shovel 2 Queue
*
****************************************************************
*

  GENERATE    ,,,1                  Create a Shovel Transaction
*                                      for East Pit (Shovel 3)
*
 ASSIGN      1,30,PH

NEXT3   QUEUE       SHOVEL3             Start SHOVEL3 Queue Membership

 TEST G      W(BACK3),0              Is There Any Trucks-XACT's
*                                         Waiting in Shovel 3 Queue ?

 DEPART      SHOVEL3                 End SHOVEL3 Membership

  SEIZE      SHOVEL3                Capture Shovel 3 Resource

  LOGIC S     SPOT3                 Shovel 3 Signals to Truck to Spot

  BUFFER                                 Shovel 3 XACT Buffers to
*                                         Let Truck-XACT Start to Spot

  BLET       &LOAD(3)=RVNORM(1,2.5,0.25)

  ADVANCE     &LOAD(3)                 Truck Loading Time at Shovel 3

  LOGIC S     LEAVE3                  Shovel 3 Signals to Truck to Leave

  RELEASE     SHOVEL3                 Free Shovel 3 Resource

  BLET       &TOTAL(3)=&TOTAL(3)+1        Update Total Loads Made by
```

```
                                                Shovel 3

BLET       &PAYLOAD(3)=&PAYLOAD(3)-1      Update Total Loads Made by

                                                 Shovel 3 Already Assigned to
                                           Shovel 3, But Not Loaded Yet

BUFFER                              Shovel 3 XACT Buffers to
*                                       Let Truck-XACT Start to Haul

 TRANSFER    ,NEXT3              Shovel 3 Returns Back to Load
*                                       Next Truck in Shovel 3 Queue
*
**************************************************************
*

GENERATE    ,,,&NUMTRK(1),5,10PH,10PL      Create  Truck-XACT's to be
*                                            Assigned to North Pit at Shift Start
*
 BLET       &TRUCKID=PH1                 Assign PH1 to Global Variable

 TEST E      AC1,0,BACK1                Is Simulation Clock at Shift Start ?

BLET       &PRODTOT(1)=&TARGET(1)          Yes, Update Total Shovel 1
*                                               Production Requirement

 BLET       &PRODNOW(1)=&TSHIFT*&PAYLOAD(1)  Update Total Truck

                                                     Assignments Made

 BLET       &RETURN(1)=RVNORM(1,4.5,0.8)

 ADVANCE     &RETURN(1)                  Truck Moves From Tie-Area to
                                              Shovel1

 TRANSFER    ,BACK1                    Transfer to Block Labeled BACK1

 GENERATE     ,,,&NUMTRK(2),5,10PH,10PL      Create  Truck-XACT's to be
*                                           Assigned to South Pit at Shift Start
*
 BLET       &TRUCKID=PH1                 Assign PH1 to Global Variable

 TEST E      AC1,0,BACK2                Is Simulation Clock at Shift Start ?

 BLET       &PRODTOT(2)=&TARGET(2)          Yes, Update Total Shovel 2
```

```
*                                                          Production
Requirement

 BLET        &PRODNOW(2)=&TSHIFT*&PAYLOAD(2)  Update Total Truck

                                                          Assignments Made

 BLET        &RETURN(2)=RVNORM(1,4.5,0.8)

 ADVANCE     &RETURN(2)                  Truck Moves From Tie-Area to

                                                   Shovel2

 TRANSFER    ,BACK2                     Transfer to Block Labeled BACK2

 GENERATE    ,,,&NUMTRK(3),5,10PH,10PL     Create  Truck-XACT's to be
*                                                  Assigned to East Pit at Shift
Start
*
 BLET        &TRUCKID=PH1                 Assign PH1 to Global Variable

 TEST E      AC1,0,BACK3                Is Simulation Clock at Shift Start ?

 BLET        &PRODTOT(3)=&TARGET(3)        Yes, Update Total Shovel 3
*                                                          Production
Requirement

  BLET        &PRODNOW(3)=&TSHIFT*&PAYLOAD(3)  Update Total Truck

                                                          Assignments Made

  BLET        &RETURN(3)=RVNORM(1,4.5,0.8)      Generate truck return

                                                          time to Shovel3

  ADVANCE     &RETURN(3)                  Truck Moves From Tie-Area to

                                                   Shovel3

 TRANSFER    ,BACK3                     Transfer to Block Labeled BACK3


BACK1   QUEUE       WAIT1                Start Queue Membership at Shovel 1

 GATE LS     SPOT1                Wait Until Shovel 1 is Free

 DEPART      WAIT1                End Queue Membership at Shovel 1
```

```
 LOGIC R      SPOT1                  Close SPOT1 Gate for Other Trucks

 GATE LS      LEAVE1                 Wait Until Truck is Loaded

  LOGIC R      LEAVE1                Close LEAVE1 Gate for Other Trucks

  BLET        &HAUL(1)=RVNORM(1,5.5,0.5)    Generate truck haul time from
*
                                                  Shovel1 to dump

 ADVANCE      &HAUL(1)                Truck Hauling Time
*                                     From Shovel 1 To Dump

  TRANSFER     ,JUMP                 Transfer to Block Labeled JUMP

BACK2   QUEUE       WAIT2                  Start Queue Membership at Shovel 2

 GATE LS      SPOT2                 Wait Until Shovel 2 is Free

   DEPART       WAIT2                End Queue Membership at Shovel 2

   LOGIC R      SPOT2                Close SPOT2 Gate for Other Trucks

  GATE LS      LEAVE2                Wait Until Truck is Loaded

   LOGIC R      LEAVE2               Close LEAVE2 Gate for Other Trucks

   BLET        &HAUL(2)=RVNORM(1,5.5,0.5)    Generate truck haul time from
*
                                               Shovel2 to dump

 ADVANCE      &HAUL(2)                Truck Hauling Time
*                                    From Shovel 2 To Dump

 TRANSFER     ,JUMP                 Transfer to Block Labeled JUMP

BACK3   QUEUE       WAIT3                  Start Queue Membership at Shovel 3

 GATE LS      SPOT3                 Wait Until Shovel 3 is Free

    DEPART       WAIT3                End Queue Membership at Shovel 3

    LOGIC R      SPOT3                Close SPOT3 Gate for Other Trucks

   GATE LS      LEAVE3                Wait Until Truck is Loaded
```

```
 LOGIC R     LEAVE3                Close LEAVE3 Gate for Other Trucks

BLET        &HAUL(3)=RVNORM(1,5.5,0.5)             Generate truck haul time

                                                     from Shovel3 to dump

 ADVANCE     &HAUL(3)                Truck Hauling Time
*                                       From Shovel 3 To Dump

JUMP    QUEUE      DUMP                  Start Waiting Time Statistics
*                                          Collected at DUMP

 ENTER       DUMP                  DUMP Resource Captured by a Truck

 DEPART      DUMP                  End Queue Membership at DUMP

 ADVANCE     RVNORM(1,1.0,0.15)         Truck Dumping Time at Dump

 LEAVE       DUMP                  DUMP Resource is Freed

 BLET        &WASTETON=&WASTETON+_    Update total waste tons
                                                dumped
                RVTRI(1,90,100,120)

 SEIZE       DISPATCH                Limit Truck Dispatching to ONE

 LOGIC S     DISPATCH                Let Dispatch-XACT Go
*                                       Through DISPATCH-Gate

 BUFFER                          Truck-XACT Buffers to Initiate
*                                     Truck Dispatching Decision

 RELEASE     DISPATCH                Truck Dispatching is Done

 TEST E      &DISPTCH,1,OTHER2         Is Truck Assigned to Shovel 1 ?

*
*************************************************************
*
*    Update Number of Trucks Assigned to Shovel 1 After A New Truck
Dispatching
*
*************************************************************
*
BLET        &PAYLOAD(1)=&PAYLOAD(1)+1   Yes, Update Trucks Assigned
to
```

```
                                                        Shovel 1

BLET        &RETURN(1)=RVNORM(1,4.5,0.8)   Generate truck return time to

                                                        Shovel1

 ADVANCE     &RETURN(1)              Truck Return Time To Shovel 1

  TRANSFER    ,BACK1                 Truck Returns to Shovel 1 Queue
*
OTHER2  TEST E      &DISPTCH,2,OTHER3       Is Truck Assigned to Shovel 2
?
*
**************************************************************
*
*     Update Number of Trucks Assigned to Shovel 2 After A New Truck
Dispatching
*
**************************************************************
*
 BLET        &PAYLOAD(2)=&PAYLOAD(2)+1   Yes, Update Trucks Assigned
to
                                                        Shovel 2

 BLET        &RETURN(2)=RVNORM(1,4.5,0.8)   Generate truck return time to

                                                        Shovel2

  ADVANCE     &RETURN(2)              Truck Return Time To Shovel 2

  TRANSFER    ,BACK2                 Truck Returns to Shovel 2 Queue
*
***************************************************************
*
*     Update Number of Trucks Assigned to Shovel 3 After A New Truck
        Dispatching
*
*
***************************************************************
**
*
OTHER3  BLET        &PAYLOAD(3)=&PAYLOAD(3)+1   No, Update Trucks

                                                        Assigned to Shovel 3

 BLET        &RETURN(3)=RVNORM(1,4.5,0.8)   Generate truck return time to
```

Shovel3

```
 ADVANCE     &RETURN(3)              Truck Return Time To Shovel 3

TRANSFER    ,BACK3                  Truck Returns to Shovel 3 Queue
*
***********************************************************
*
*     TRUCK DISPATCHING DONE AFTER DUMPING
*
*     WITH MINIMIZING SHOVEL PRODUCTION TARGET RULE
*
*     SINGLE TRUCK DISPATCHING IS DONE AT ANY TIME
*
*************************************************************
***

GENERATE    ,,,1,10,10PH,10PL                 Create a Single
*                                                 Dispatch-Transaction
*
BACK   GATE LS     DISPATCH            Wait Until A Truck
*                                       Needs to be Dispatched ?
*
 BLET       &PRODTOT(1)=AC1*&TARGET(1)

 BLET       &PRODNOW(1)=&TSHIFT*(&TOTAL(1)+&PAYLOAD(1))

 BLET       &DSPCH(1)=&PRODTOT(1)/&PRODNOW(1)

  BLET       &PRODTOT(2)=AC1*&TARGET(2)

  BLET       &PRODNOW(2)=&TSHIFT*(&TOTAL(2)+&PAYLOAD(2))

  BLET       &DSPCH(2)=&PRODTOT(2)/&PRODNOW(2)

   BLET       &PRODTOT(3)=AC1*&TARGET(3)

   BLET       &PRODNOW(3)=&TSHIFT*(&TOTAL(3)+&PAYLOAD(3))

   BLET       &DSPCH(3)=&PRODTOT(3)/&PRODNOW(3)

   ASSIGN      1,&DSPCH(1),PL          Assign &DSPCH(1) to PH1

   ASSIGN      2,&DSPCH(2),PL          Assign &DSPCH(2) to PH2

    ASSIGN      3,&DSPCH(3),PL          Assign &DSPCH(3) to PH3
```

```
   SELECT MAX   10PH,1,3,,PL            Find Maximum of Parameters 1
through 3

    BLET        &DISPTCH=PH10           Assign Value of Parameter 10
*                                         to Global Variable &DISPATCH

   LOGIC R      DISPATCH                Close DISPATCH-Gate

  TRANSFER      ,BACK                   Dispatch-XACT Returns
*                                        Back for New Assignments
*
*****************************************************************
*
*
*      TIMER-TRANSACTION SECTION
*
*****************************************************************
*
*
 GENERATE    &TSHIFT             Timer Transaction at 480 minutes

  TERMINATE    1
*
*****************************************************************
*
*
*      MULTIPLE-RUN CONTROL SECTIONS
*
*****************************************************************
**
*
      DO         &I=1,10                10 Replicates are done
      CLEAR
      START       1                    Single Run is made

      LET        &NUMTK=&NUMTRK(1)+&NUMTRK(2)+&NUMTRK(3)

      LET        &TOT1=&TOT1+FR(SHOVEL1)/10.
      LET        &TOT2=&TOT2+FR(SHOVEL2)/10.
      LET        &TOT3=&TOT3+FR(SHOVEL3)/10.
      LET        &TOT4=&TOT4+QT(WAIT1)
      LET        &TOT5=&TOT5+QT(WAIT2)
      LET        &TOT6=&TOT6+QT(WAIT3)
      LET        &TOT7=&TOT7+QT(DUMP)

      LET        &PAY1(&I)=N(NEXT1)
      LET        &PAY2(&I)=N(NEXT2)
```

```
LET        &PAY3(&I)=N(NEXT3)
LET        &TPAY(&I)=N(NEXT1)+N(NEXT2)+N(NEXT3)
LET        &SWAIT1(&I)=QT(WAIT1)
LET        &SWAIT2(&I)=QT(WAIT2)
LET        &SWAIT3(&I)=QT(WAIT3)
LET        &DWAIT(&I)=QT(DUMP)

LET        &TWAIT1(&I)=&PAY1(&I)*&SWAIT1(&I)
LET        &TWAIT2(&I)=&PAY2(&I)*&SWAIT2(&I)
LET        &TWAIT3(&I)=&PAY3(&I)*&SWAIT3(&I)
LET        &TWAITD(&I)=&TPAY(&I)*&DWAIT(&I)

LET        &TTWAIT(&I)=&TWAIT1(&I)+&TWAIT2(&I)+_
           &TWAIT3(&I)+&TWAITD(&I)

LET        &TUTIL(&I)=((480.0*&NUMTK-

           &TTWAIT(&I))/(480*&NUMTK))*100

LET       &SUTIL(&I)=(FR(SHOVEL1)+FR(SHOVEL2)+

          FR(SHOVEL3))/30.

LET        &TLOAD(&I)=N(NEXT1)+N(NEXT2)+N(NEXT3)

IF        (&NUMTK=9)
PUTPIC     FILE=OUT2,(&I,&SUTIL(&I),&TUTIL(&I),&TLOAD(&I),'2')
**      **.**      **.**      ***    *
ELSEIF     (&NUMTK=15)
PUTPIC     FILE=OUT3,(&I,&SUTIL(&I),&TUTIL(&I),&TLOAD(&I),'2')
**      **.**      **.**      ***    *
ELSE
PUTPIC     FILE=OUT4,(&I,&SUTIL(&I),&TUTIL(&I),&TLOAD(&I),'2')
**      **.**      **.**      ***    *
ENDIF
ENDDO

LET        &AVE1=&TOT1/10.00
LET        &AVE2=&TOT2/10.00
LET        &AVE3=&TOT3/10.00

LET        &AVSUTIL=(&AVE1+&AVE2+&AVE3)/3

LET        &AVE4=&TOT4/10.00
LET        &AVE5=&TOT5/10.00
LET        &AVE6=&TOT6/10.00
LET        &AVE7=&TOT7/10.00
```

```
     LET        &TOTAL(1)=&TOTAL(1)/10.
     LET        &TOTAL(2)=&TOTAL(2)/10.
     LET        &TOTAL(3)=&TOTAL(3)/10.
     LET        &WASTETON=&WASTETON/10.

     LET        &TOTL=&TOTAL(1)+&TOTAL(2)+&TOTAL(3)

     LET        &TOTWAIT(1)=&TOTAL(1)*&AVE4
     LET        &TOTWAIT(2)=&TOTAL(2)*&AVE5
     LET        &TOTWAIT(3)=&TOTAL(3)*&AVE6

     LET        &TOTWAIT(4)=&TOTL*&AVE7

     LET        &TOWAIT=&TOTWAIT(1)+&TOTWAIT(2)+_
              &TOTWAIT(3)+&TOTWAIT(4)

     LET        &UTIL=((480.0*&NUMTK-&TOWAIT)/(480*&NUMTK))*100
*
*************************************************************
*
*     Write User-Specified Output Statistics to Output File
*
**************************************************************
*
     PUTPIC
LINES=17,FILE=OUT1,(&NUMTK,&AVE1,&AVE2,&AVE3,_
              &TOTAL(1),&TOTAL(2),&TOTAL(3),_
              &TOTL,&WASTETON,&AVE4,&AVE5,&AVE6,&AVE7,_
              &UTIL,&AVSUTIL)
|----------------------------------------------------------------------|
|     TOTAL NUMBER OF TRUCKS IN THE MINE          : ***   (Trucks)    |
|     SHOVEL1 UTILIZATION                    : **.**%          |
|     SHOVEL2 UTILIZATION                    : **.**%          |
|     SHOVEL3 UTILIZATION                    : **.**%          |
|     TOTAL NUMBER OF TRUCK LOADS MADE BY SHOVEL 1    : ***
(Loads)    |
|     TOTAL NUMBER OF TRUCK LOADS MADE BY SHOVEL 2    : ***
(Loads)    |
|     TOTAL NUMBER OF TRUCK LOADS MADE BY SHOVEL 3    : ***
(Loads)    |
|     TOTAL NUMBER OF TRUCK LOADS MADE BY ALL SHOVELS : ***
(Loads)    |
|     TOTAL TONNAGE MADE BY ALL SHOVELS            : *****  (Tons)
|
|     AVERAGE TRUCK WAITING TIME AT SHOVEL 1         : **.**  (Min)
|
```

```
|      AVERAGE TRUCK WAITING TIME AT SHOVEL 2          : **.**  (Min)
|
|      AVERAGE TRUCK WAITING TIME AT SHOVEL 3          : **.**  (Min)
|
|      AVERAGE TRUCK WAITING TIME AT DUMP            : **.**  (Min)
|
|      OVERALL TRUCK UTILIZATION                    : **.**%          |
|      AVERAGE SHOVEL UTILIZATION                    : **.**%          |
|---------------------------------------------------------------------------|

      END
```

VITA

Necmettin ÇETIN was born in Serik-Antalya on February 10, 1967. He has received his B.Sc. degree in the Department of Mining Engineering from Middle East Technical University in 1989. He also has received his M.Sc. degree from the same university in 1992 at the same department. He worked for a consulting company named TUSTAS in Ankara when he was a graduate student. He has been a research assistant in the Department of Mining Engineering at Dumlupınar University since 1994. His main areas of interest are computer applications in mining, statistics and simulation modeling.