

SIMULATION OF PRODUCT TRANSPORTATION IN OPEN PIT MINES

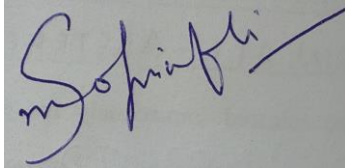
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Environment, University of Witwatersrand, Johannesburg, in
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in Engineering

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DECLARATION

I declare that this research report is my own unaided work. It is being submitted for the degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

A handwritten signature in blue ink, appearing to read 'Sofia', with a long horizontal stroke extending to the right.

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ABSTRACT

Open pit mines account for more than 60 percent of all surface mines, and haulage costs account for almost 60 percent of total operating costs for these mines. It necessitates maintaining an efficient haulage system where all fleet equipment performs effectively to achieve the mine's objectives. Discrete event simulation supported by animation offers a powerful method for evaluating such systems. This research has developed a simulation software program using Visual Basic for Application (VBA), GPSS/H (General Purpose Simulation System), and PROOF 5 animation. Remaining within the defined assumptions and boundary conditions, the research combines the powers of three software languages to build a general-purpose, data-driven, and user-friendly simulation program. The research focuses on the study and simulation of some of the important complexities of the truck haulage system. These include uncertainty or system randomness, fleet heterogeneity, multi-loader multi-dump sites, bunching of haulers, and hauler dispatching. In the developed simulation program, the user is required to provide the inputs in the user-friendly environment of VBA. The simulation program arranges the inputs in a pre-arranged format and then sends them to GPSS/H. The simulation language generates a discrete event simulation model based on the receiving structural and operational data. After simulating the system, the model generates the simulation outputs and animation commands in separate files. VBA displays a summary of the simulation results, and PROOF 5 demonstrates the results in a 2-dimensional graphical animation along with detailed information. This research also includes three case studies based on hypothetical mines for the analysis of simulation results. It establishes comparisons between the dispatching policies of fixed allocation and variable allocation of Minimize Production Requirements (MPR), and shows that the MPR policy is more suitable to achieve the quality control objectives. The developed simulation program contributes by demonstrating the powers of simulation to analyse open pit haulage systems. It also shows how simulation can be utilized as a useful technique to answer many 'what-if?' questions and scenarios.

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Contents	Page
DECLARATION	i
ABSTRACT	ii
ACKNOWLEDGMENT	iii
LIST OF FIGURES	vii
LIST OF TABLES	viii
LIST OF ABBREVIATIONS	ix
LIST OF DEFINITIONS	xi
1 INTRODUCTION	1
1.1 Chapter Overview	1
1.2 Problem Statement and Motivation	1
1.3 Systems, Models and Simulation	2
1.4 Animation	4
1.5 Scope of the Research	5
1.5.1 Significance of the Research	5
1.5.2 Objectives of the Research	6
1.5.3 Structure of the Research	8
2 LITERATURE REVIEW	10
2.1 Chapter Overview	10
2.2 Mine System Simulations – Past, Present, and the Future	10
2.3 Simulation Tools	16
2.4 Conclusion	18
3 TRUCK HAULAGE SYSTEM	20
3.1 Chapter Overview	20
3.2 Load-Haul-Dump Cycle	20
3.3 Considerations for Simulating Truck Haulage System	22
3.3.1 Uncertainty	23
3.3.2 Heterogeneous Fleet	24
3.3.3 Multi-loader, Multi-dump Sites	24

3.3.4	Bunching of Haulers	25
3.3.5	Hauler Dispatching	26
4	DESIGN METHODOLOGY OF THE SOFTWARE PROGRAM	28
4.1	Chapter Overview	28
4.2	Selection of Tools	28
4.2.1	GPSS	29
4.2.2	PROOF	29
4.2.3	VBA	30
4.3	Design Concept of the Software Program	30
4.3.1	Information Flow Architecture	31
4.3.2	Assumptions and Constraints	33
4.4	User Inputs	34
4.5	Outputs of the Software Program	38
4.6	Conclusion	40
5	FUNCTIONAL METHODOLOGY OF THE SIMULATION MODEL	42
5.1	Chapter Overview	42
5.2	Simulation Model Overview	42
5.3	Input Data Sets for the Simulation Model	44
5.4	Sub-model Structures	49
5.4.1	Breakdowns	50
5.4.2	Bunching of Haulers	51
5.4.3	Hauler Dispatching	52
5.5	Output Data Sets of the Simulation Model	54
5.6	Conclusion	56
6	ANALYSIS OF RESULTS	57
6.1	Chapter Overview	57
6.2	Case Study 1	57

6.3	Case Study 2	60
6.4	Case Study 3	65
6.4.1	Scenario A	65
6.4.2	Scenario B	68
6.5	Conclusion	70
7	SUMMARY AND CONCLUSION	71
7.1	Summary	71
7.2	Conclusion	72
7.3	Future Work	72
	REFERENCES	74
APPENDIX A:	Case Study 1: Input Parameters for the Simulation Program and FPC	80
APPENDIX B:	Case Study 2: Input Parameters for the Simulation Program	82
APPENDIX C:	GPSS/H Code	84
APPENDIX D:	Electronic Version of the Simulation Software Program (CD)	104

LIST OF FIGURES

Figure	Page
3.1 Load-haul-dump cycle	21
4.1 Information flow architecture	32
4.2 Distribution of the times during a shift	37
4.3 Screenshot of inputs – mine layout and parameters (example)	37
4.4 Screenshot of graphical input for mine layout (example)	38
4.5 Screenshot of simulation results (example)	39
4.6 Screenshot of animation (example)	40
5.1 General structure of the simulation model	49
6.1 Mine layout – case study 2	60
6.2 Difference between achieved production and target production for ore, waste, and each location – case study 2	63
6.3 Tonnage transported by each hauler – case study 2	64
6.4 Difference between achieved production and target production for ore, waste, and each location – case study 3 (scenario A)	66
6.5 Tonnage transported by each hauler – case study 3 (scenario A)	66
6.6 Difference between achieved production and target production for ore, waste, and each location – case study 3 (scenario B)	68
6.7 Tonnage transported by each hauler – case study 3 (scenario B)	69

LIST OF TABLES

Table	Page
4.1 Input parameters for the software program	36
5.1 Input data sets for the simulation model	46
5.2 Brackets of ID numbers for each facility/ storage	51
5.3 Output data sets managed by simulation model	53
6.1 Parameters of FPC example – case study 1	57
6.2 Outputs of simulation program – case study 1	58
6.3 Results for fixed allocation – case study 2	61
6.4 Results for variable allocation – case study 2	62
6.5 Parameters of the loaders – case study 3 (scenario A)	65
6.6 Parameters of haulers – case study 3 (scenario B)	67

LIST OF ABBREVIATIONS

ATF file	Animation Trace File (used in P5 software)
C	Crusher
C_n	Total number of crushers
CPOH	Cost Per Operating Hour
CPT	Cost Per Ton
D	Dump site
D_E	Distance travelled by Empty hauler (in km)
D_L	Distance travelled by Loaded hauler (in km)
D_n	Total number of dump sites
EW_{FT}	Empty hauler Weight on Front Tyre
FIFO	First In First Out
GPSS	General Purpose Simulation System
GUI	Graphical User Interface
H	Hauler
H_n	Total number of haulers
ID	Identification
K_D	Dispatching parameter to find the dump site that is most lagging in production
K_L	Dispatching parameter to find the loader that is most lagging in production
L	Loader
L_n	Total number of loaders
LW_{FT}	Loaded hauler Weight on Front Tyre
LAY file	Layout File used in P5 software
MPR	Minimize Production Requirement
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
OEM	Original Equipment Manufacturer
OSR	Overall Stripping Ratio
P5	Proof version 5 software (used for 2-dimensional animation)
P_n	Total number of paths (road sections)

R_n	Total number of routes between all loading and unloading points
S_E	Speed of Empty hauler
S_L	Speed of Loaded hauler
TKPH	Ton Kilometre Per Hour
TPOH	Ton Per Operating Hour
VBA	Visual Basic for Application
W	Waste dump
W_n	Total number of waste dumps

LIST OF DEFINITIONS

Crusher: A plant or a machine used to reduce the size of run-of-mine ore material. It usually has an input stockpile and an output stockpile.

Dump site: A crusher, waste dump, or stockpile.

Hauler: A mining truck, also known as haul truck or road truck that haul the material (ore or waste) from the loader to a dump site.

Loader: A high productivity piece of equipment capable of excavating soft, loose material and blasted rock, which may include a mining loader, excavator, or shovel etc.

Non-operating delays: The time during which engine of the equipment is OFF.

Operating delays: The time during which engine of the equipment is ON, but the equipment is not operating in its designated haulage cycle.

Operating duration: It is the duration of shift during which equipment does not face any non-operating delays.

Path: A road section that bears uniform road characteristics and profile (rolling resistance, grade-ability etc).

Route: A combination of paths connected with each other, at one end of which is a loader and on other end is a dump site.

Waste dump: A site to dump or stockpile the waste material.

Working duration per shift: It is the portion of the shift during which equipment does not face any operating or non-operating delays.

CHAPTER 1

INTRODUCTION

1.1 Chapter Overview

Surface mining is an old and popular mining method, utilized in the conditions when ore (mineral endowed rock) is close to surface. There are various methods of surface mining including open pit, open cast or stripping, mountain-top removal, and dredging. Surface mining includes product transportation systems which play the most cost-contributing role in the mining operations.

The research focuses on presenting the effectiveness and power of simulation technology for analysis of open pit haulage systems. This chapter introduces the problem statement and motivation, and describes the basics of simulation technology and scope of research.

1.2 Problem Statement and Motivation

Open pit mines constitutes more than 60% of all surface mines (Hartman and Mutmanský, 2002). It is a cut made at ground level for the purpose of extracting ore, and it remains open to the surface for the duration of mine's life (Hartman, 1992). In a deep-surface open-pit mine, waste (overlying soil) is removed and haul roads are constructed to carry out the ore extraction (Newman et al, 2010). The transportation of material is carried out using a system of loaders (shovels, excavators etc) and haulers (trucks). The loaders load the haulers, and the haulers transport the material to a dumping location at the crusher, waste dump or stockpile. The haulers then return to the loaders and the cycle repeats itself. Open pit mines employ power shovels to load excavated material into the haulers. Often the material is removed by blasting; however some mines also use shovel-truck system to excavate bedded type deposits (Czaplicki, 2009).

The truck haulage system is the most common method of transporting ore and waste in an open pit mine. The system offers comparative advantages in relation to in-pit crushing and conveying, railway tracks etc, due to high mobility,

flexibility, climbing ability, small turning radius, and less investment in infrastructure (He et al., 2010). At the same time, it can be very costly and may constitute up to 60% of total mining cost (Li, 1990; Niemann-Delius and Fedurek, 2004).

The high operating costs of truck haulage systems forces mine management to keep evaluating the strategies and reduce the overall cost of material handling. During each phase of mine development, correct fleet selection must also be ensured to optimize the mine operations and production throughput. Recently, this is receiving more attention in open pit haulage systems to improve the mining equipment efficiency (Parreira and Meech, 2012).

Amongst various strategies to evaluate open pit haulage systems, computerized simulation techniques have proved to be a powerful and well used tool (Brown et al., 1988; Christina, 2008; Hall, 2000). It has also been used effectively for mine design, planning, and optimization (Tarshizi, 2012).

1.3 Systems, Models and Simulation

A *System* is defined as “a collection of entities, e.g., people or machines, which act and interact together toward the accomplishment of some logical end” (Law and Kelton, 1982). A *model* is a plan, pattern, representation or description designed to show the working or structure of a system (Czaplicki, 2009). And, *simulation* is the process of designing a model of a real system to understand its behaviour and evaluate various strategies for the operation of the system within the limits imposed by a criterion or set of criteria (Sturgul, 1999).

The *System* is usually the facility or process of interest, which requires a set of assumptions to study its working. The assumptions which take the form of logical, symbolic, and mathematical relationships constitute a *model* (Law and Kelton, 1982; Salama, Greberg and Schunnesson, 2014). The models are approximations of real things that are built to achieve a specific purpose (Hall, 2000). If the relationships composing the model are simple enough to allow the mathematical methods (e.g. calculus, algebra or probability theory) obtain the desired

information, it is called an analytical solution (Law and Kelton, 1982). If, however, the system is complex, as many real world systems are, then the model must be studied through simulation. The *simulation* uses a computer to evaluate a model numerically over a defined duration, in order to estimate the desired true characteristic of the model.

A system can be continuous or discrete in nature (Law and Kelton, 1982). The continuous system is one where events occur or state variables change continuously with respect to time ((Salama, Greberg and Schunnesson, 2014). The modelling of continuous systems generally involves differential equations that give relations for the rates of change of the variables (Yuriy, 2005). A flying airplane represents a continuous system, as the position and velocity change constantly with time. In a discrete system, the events occur or “state variables change only at a countable number of points in time” (Law and Kelton, 1982). A barber shop is an example of discrete system, where the numbers of customers present in the shop changes only when a customer arrives or departs the shop. The performance of a discrete segment does not depend on the performance of previous segment (Tarshizi, 2012). For the barber shop example, the time taken to undertake a hair cut does not depend on the time taken by customer to wait in queue.

A model can be of various types such as physical models, spreadsheet models, and simulation models. The boundaries and level of detail in the model play a vital role in identifying the accuracy of the generated results (Hall, 2000). This research focuses on the ‘simulation model’ which represents a particular type of mathematical model of a system. A simulation model can be categorized on the basis of the system types i.e. discrete or continuous; it can also be classified as static or dynamic and deterministic or stochastic. A static simulation model represents a system at a particular time, and a dynamic simulation model represents a system as it evolves over time (such as activities of a barber shop over a 12 hour shift). A simulation model is deterministic if it has no random variables, and it is stochastic if it has one or more random variables (Law and Kelton, 1982).

For the purpose of this research, the terminology ‘discrete event simulation model’ corresponds to the discrete, dynamic, and stochastic simulation model. Discrete event simulation is a proven tool in the analysis and design of a complex system that helps in drawing the conclusions about the system performance (Alemparte et al., 1975). It represents systems that have a chronological sequence of events. Examples are traffic flows, mining operations, barber shops and ports etc. The major advantages of discrete event simulation include flexibility to model a system with different levels of detail and complexity, and modelling of a dynamic system with uncertainties. Contrarily, estimations in the produced outputs and high dependence on the statistical data are the major disadvantages (Tarshizi, 2012).

A data driven model is the one which can be applied to the systems with similar structures (Runge, 1983). In comparison to typical models, the data driven modelling approach offers low development time and cost, since the use of program is independent of model development (Franz, 1989).

1.4 Animation

Animation translates the simulation models into visuals, through which the user can see the identifiable elements moving or working in a realistic system. It helps in problem identification and its analysis in an overall picture, thus leading to better planning and optimization (Sturgul and Li, 1997; Tarshizi, 2012).

Animation is a powerful communication tool (Alemparte et al., 1975) that can be used with a specialized simulation language. It depicts the activity of equipment or entities on the screen. In the animation section, the user has the option to enlarge any part of the process, collect the statistical data, and jump forward or backward in time to analyze the situation (Konyukh, Galiyev and Li, 1999).

Animation enhances the effects produced by the simulation model. If one wants to alter a simulation model to improve its performance, firstly he or she must step inside the model and watch it perform as the real system might perform. It leads to a reasonably smooth and meaningful dialogue between the user and the model

(Alemparte et al., 1975), helps in detecting design flaws and gaining confidence in the effectiveness of system (Sturgul and Li, 1997).

Animation also plays an important role in the verification and validation process (Castillo and Cochran, 1987; Sturgul and Li, 1997), as it provides the ability to see a simulation model in action. *Verification* is checking the correctness of computer code, after the simulation model is programmed. For a dynamic system, the analyst must use animation to detect the programming errors (Kleijnen, 1995). A vehicle passing through other vehicles due to its fast travel speed is an example of such an error. *Validation* checks the conceptual simulation model (and not the computer program) with the system under study (Kleijnen, 1995). Animation helps to a reasonable extent, in determining whether the model reflects the reality of an existing or proposed system (Sturgul and Li, 1997).

1.5 Scope of the Research

1.5.1 Significance of the Research

Experimentation is a critical component of scientific method. At times, extensive experimentation is difficult or impractical in many industrial systems. Due to the large magnitude of mining operations, the mineral industry presents one such case. This is where simulation can be used effectively because of its inherent power to model and experiment with the reality (Cross and Williamson, 1969).

The use of simulation techniques offers many advantages including realistic behaviour estimation (Hall, 2000), time compression or expansion, understanding of non-existent systems, identification of system constraints (Sturgul and Li, 1997), reproducibility of various conditions, experimental control, and ease of training (Schriber, 1991). These can provide useful results when simple analytical solutions cannot be calculated and components in the overall mining system interact in a complex manner. The limitations of mine simulation include failure to produce exact results, inability to provide fast easy answers to complex questions and high costs of development. It cannot directly optimize the mining system, yet it is capable to answer many ‘what-if?’ questions. Simulation results

are highly dependent on the accuracy of input parameters and modelling characteristics of mining system (Alemparte et al., 1975; Hall, 2000)).

Discrete event simulation provides powerful decision support to the truck haulage system operating in a variable mining environment (Salama, Greberg and Schunnesson, 2014), as it is effective in capturing the high degree of complexity (Meng et al., 2013). The dynamic and interlinked nature of mining operations shows that the mines can effectively use the discrete event simulation associated with animated visuals. It can handle the uncertainties of mining operations to answer many ‘what-if’ questions that are difficult to be predicted by direct means.

One can model an extremely complex system to a requisite degree of accuracy, if it can be described accurately. The stochastic random behaviour features are helpful in estimating the average performance and likely variability (Hall, 2000). The random number selection method creates probability distributions from the time studies data. It generates sequence of variable times expected to occur during actual operations, which the modeller can use to find values for the sections of the haul cycle (Deshmukh, 1970). Due to the dynamic and stochastic nature of loader-hauler interaction, different simulation models used for fleet optimization may yield different fleet sizes for the same inputs. It is due to the assumed probability distributions applied to the variables of cycle time (Krause, 2006; May, 2012).

A complete picture of a mine system can be viewed by combining the statistically valid mine simulation model with the visual power of animation. Animation highlights the things that are otherwise difficult to catch using just the mine simulation model. Though animation does not directly assist the modelling process, it represents the results and verifies the correctness of a mine system simulation model.

1.5.2 Objectives of the Research

The research aims at developing a discrete event simulation model for product transportation (waste and ore) in an open pit mine. It contributes in proving that a simulation technique supported by animation is a powerful tool helpful in

considering various scenarios and finding the best possible solution for product transportation in an open pit mine.

This research presents a data-driven model of an open pit haulage system with due considerations to the stochastic properties, haulage conditions and equipment parameters. It offers a simulation software program that allows the user to provide the variables as per the planned or existing mine parameters. The software program operates using an animated discrete event simulation model where animation provides a visual appreciation of the system's behaviour. The research also analyses the generated outputs with due regards to the assumptions and boundary conditions of the model.

The developed software program generates the discrete event simulation based on the user-defined transportation structural and operational data. The program uses Visual Basic for Applications (VBA) to develop a Graphical User Interface (GUI) with a formal information model. The General Purpose Simulation System (GPSS) procedures carry out the simulation based on the inputs received from VBA. It uses PROOF software for the animation which imports mine layout data from VBA and simulation data from GPSS to demonstrate the resultant animation.

The main objective of the research is to develop a user-friendly data-driven software program to represent the simulation and animation of an open pit haulage system. The subject entails various aspects and a number of variables and interdependent complexities; all of which are often difficult to be addressed in a data-driven simulation model. It is an acceptable engineering practice in simulation modelling to define a set of assumptions and boundary conditions. The scope of this research restricts itself to work under following levels of detail and boundary conditions: -

- The model is applicable for short to medium term plans, and deals with single stage materials handling systems. The simulation model incorporates the uncertainties of mining systems to a reasonable level. The software assumes that the user has carried out substantial time studies of a load-haul-dump cycle, and provides the statistical data best fit to the real system. The model

implements normal distributions for all the haulage activities, and exponential distributions for the breakdowns of loaders, haulers, and dump sites. It simulates the system on the shift-duration basis, and also incorporates the effects of operator's efficiency on the cycle times.

- The model generates the effects produced by a heterogeneous fleet operating in the mine. It takes into account the mixed types of haulers and loaders having different operational parameters.
- The model is capable of dealing with multi-loader multi-dump sites linked through a complex road network. It also handles the production of ore and waste in the mine at the same time.
- The mixed fleet, variability of haulers travel times, and junctions (intersections) in the road network may produce bunching of haulers. The software program addresses this important aspect in the simulation model.
- The simulation model operates the mining system based on variable and fixed allocation of haulers. The research implements the variable allocation policy of 'Minimize Production Requirements (MPR)', and compares the results with fixed allocation system.

1.5.3 Structure of the Research

The research report is divided into seven chapters including the introduction. Chapter 2 gives a detailed literature review on the simulation methods applied in mining industry, and assesses the extent to which these methods address the open pit haulage systems. Chapter 3 evaluates the load-haul-dump-cycle of a truck haulage system. The chapter also discusses the complexities involved in the system that affect the accuracy of the simulation model. These include uncertainty, heterogeneity, multi-loader multi-dump sites, bunching, and dispatching. Chapter 4 explains the design and development methodology of the simulation software program. It gives details on the features of adopted tools and discusses how these are integrated to develop the desired program. The chapter also illustrates the assumptions and constraints of the software program along with the details on user inputs and outputs. Chapter 5 presents the functional methodology of the simulation model, and illustrates how the user inputs

transform into the arranged data sets in the model. The chapter also discusses the sub-model structures and the output data sets managed by the simulation model. Chapter 6 considers three case studies on hypothetical mines, and analyses the results generated by simulation software program. The main comparisons are drawn between fixed and variable allocation systems. Finally, Chapter 7 concludes the research report, and recommends areas of future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Overview

Many aspects of the mining industry have received the attention of computer simulations since the 1960's (Brown et al., 1988; Sturgul and Li, 1997). However, the development of simulation software specific to the mining industry lagged behind considerably when compared to other industries. The available capital to support a simulation analysis and lack of technical expertise hindered its wide application. Large scale and technically sophisticated mining operations remained the major recipients of truck haulage simulations, as they had the capability to justify the modelling and implementation costs of computers, simulation software, technical staffing and consulting charges (Castillo & Cochran, 1987).

With time mine management started accepting the simulation applications, and in the past decade the industry developed the simulation and animation models rapidly in many fields. Now various mines are using simulation models of production schedules, equipment fleet size, layout, and operating rules to analyze their operations (Tarshizi, 2012). The studies related to haulage system simulations covered most of the important issues in operating and managing the truck fleet of a mine. The industry applied these studies in long term decision making for equipment selection, cost analyses, hauler-loader matching, optimization, and long term productivity predictions. For short-to-medium term, the simulation techniques displayed its positive effects for crusher/ dump allocation, route planning, and hauler dispatching (Sturgul, 1987; Zhang, Kinnane & Rogers, 1994).

2.2 Mine System Simulations – Past, Present, and the Future

The application of simulation techniques in mining problems started as early as the 1960s (Brown et al., 1988; Sturgul and Li, 1997). The University of Arizona in Tucson, AZ held the first APCOM (Application of Computer and Operations Research in Mining) symposium on use of computers in the mining industry in

1961 (Czaplicki, 2009; Sturgul, 1999). The literature recognizes the work by Rist (1961) as the first published contribution of computer simulation of a mining operation (Sturgul, 2001; 1999), where he used SPS (Symbolic Program System) language to determine the optimum number of trains in an underground mine. Later, Harvey (1964) extended Rist's work by using GPSS (General Purpose Simulation System) language, which became the first published application of GPSS to a mining operation (Sturgul, 1999).

O'Neil and Manula (1967) and Cross and Williamson (1969) performed computer simulation for an open pit truck haulage system. The model developed by O'Neil and Manula recognized the probabilistic nature of certain service times in order to handle the complex systems of multiple mine faces and multiple destinations. The standard simulation of truck movements allowed each hauler to perform according to mechanical capability and haul road profile. Cross and Williamson analysed the benefits of introducing the dispatcher for a truck-shovel operation. The simulation model assumed the deterministic timings for the system, and indicated that dispatching would improve the savings. Deshmukh (1970) used simulation techniques to study the load-haul-dump cycle for the fleet sizing in open pit mines. He assumed lognormal distribution of times for the loading, dumping and delays occurring during haul and return. The haul and return times were treated as deterministic and hence assumed constant.

From 1970s, the use of discrete simulation gained recognition in many countries (Konyukh, Galiyev and Li, 1999). In this regards, Conell's SME Mining Engineering Handbook (1973) contributed comprehensively in presenting the benefits of stochastic simulation. Bauer and Calder (1973) explained the complexity of modern open pit haulage systems. They discussed both the standard and probabilistic simulation procedures, and indicated probabilistic simulation as a more powerful and practical technique.

By 1980, the mining industry established that simulation models could contribute a lot towards the determination of optimal truck fleet size and dispatching strategy. Here, the works by Brake and Chatterjee (1979), Hauck (1979), and Ibarra and Kim (1980) are worth mentioning. The research by Brake and

Chatterjee focused on the development of an interactive model of a large open pit mine under the broader concepts of probabilistic simulation and information storage methodology. The research by Hauck discussed the real time automatic dispatching of haulers to loaders, with the help of radio signals and digital display units placed in the truck cabins. And, the research by Ibarra and Kim compared the existing operation with dispatch mode operation, and showed the improvement in productivity with dispatching by approximately 10%.

Wilke and Heck (1982) improved the simulation models developed by Brake and Chatterjee, Hauck, and Ibarra and Kim. They incorporated additional features to handle the special problems of truck haulage dispatching, which included maximising the truck fleet utilization and maintaining ore blending ratio. They also implemented the different speeds of haulers, actual layout of haul road networks (intersections, crossings etc), possible queuing at loaders and dump locations, and stochastic influences in the simulation model. The original model was developed for the Bong Mine, Liberia.

Lizotte and Bonates (1987) used stochastic simulation program to analyse the dispatching rules applicable to small scale computerized systems. The study demonstrated an increase in productivity by the use of dispatching rules at semi-automated dispatching systems. In 1988, they modified their computer simulation model to study the continuous dispatching of trucks in open pit mines. The model performed an active role by suggesting the best assignment according to specific conditions (Bonates and Lizotte, 1988).

Castillo and Cochran (1987) presented a microcomputer system approach to simulate the truck haulage system in open pit mines. They used SLAM II and FITPLUS for simulation and statistical analysis of mining methods, and discussed the issues concerning simulation and statistical software, processing times and implementation costs. Sturgul and Yi (1987) introduced a more complicated model based on Cross and Williamson's model. They incorporated stochastic times for various operations in surface coal mines, which helped in proving the power of GPSS language for mine system simulations. In the same year, Sturgul (1987) also presented a simplified simulation example to determine the optimum

location of in-pit movable crushers. He presented the solution in GPSS language to find the optimum number of trucks and most feasible crusher location out of the three optional locations.

Overall, the 1980s saw a substantial growth in the applications of computer techniques to truck haulage systems. The applications addressed the operating and management aspects related to dispatching, haul route planning, and equipment allocation (Zhang, Kinnane & Rogers, 1994). By 1995, various authors around the world published or presented approximately 150 papers on mine system simulations. These included both the actual mine simulation reports and theoretical examples (Sturgul, 1999). The simulation industry established haulage system simulations based on PC software that did not require any specialized hardware. The methodology developed its base on random variations constrained by underlying distribution of probable occurrences for loader cycle time, hauler travel time, and delays etc. The results of the calculations generally included productivity (per operating hour, shift or year), average payloads, and hauler travel and queuing times (Zhang, Kinnane & Rogers, 1994).

The haulage system simulations developed in the 1990s progressed further with the introduction of computer software products, examples being TALPAC developed by Runge Mining and FPC (Fleet Production and Cost program) developed by Caterpillar Inc. TALPAC used stochastic simulations with probability distributions fitted to cycle components. The simulation model of TALPAC incorporated the haul road conditions and other operational parameters including travel, queuing, loading and cycle times, truck and loader productivity, fuel usage, and material unit costs (Zhang, Kinnane & Rogers, 1994). FPC, on the other hand, utilized regressive modelling techniques that can also be regarded as static simulation algorithms. The program takes waiting time as a function of fleet matching and bunching correction factors. It is widely used as the first method to establish a potential customer's fleet requirements (Krause, 2006).

In 1995, Jacobsen et al (1995) developed a simulation model integrated with visual animation for waste handling at Lihir Project in Papua New Guinea. They used GPSS/H for the simulation model and PROOF for the animation. They

believed it to be the first application of an animated simulated study for the mine planning. In 1998, Kazakh National Technical University, Kazakhstan simulated a product transportation system involving factors like reliability, utilization and several combinations of equipments to evaluate optimum structure of transport network (Konyukh, Galiyev & Li, 1999).

Sturgul, in 2000, published a significant book on the application of simulation techniques on the mine design. The book ‘Mine Design – Examples using Simulation’ provided comprehensive details on the use of GPSS language (Sturgul, 2000). In 2004, Çetin (2004) developed a stochastic truck dispatching and production simulation model supported with animation. In his PhD research, Çetin used GPSS/H software to analyse the eight basic truck dispatching rules, and searched for a hybrid rule applicable to open pit mines. The assumptions of the simulation model included a single material, single dump site, single dump point at dump site, homogeneous fleet of trucks and shovels, trucks allowed to overtake each other, and truck failure only checked after dumping. In the following year, Yuriy (2005) used discrete event simulation modelling along with a reliability assessment model to assess the impacts of equipment failure. He developed two models using AutoMod and Simul8 to compare the results.

Krause (2006) investigated the main factors of production, their interaction and influence on the cycle time efficiency for the truck haulage systems. He also examined various probability distributions used to model particular cycle time variables. The study compared the characteristics of Elbrond, FPC (Fleet Production and Cost model), TALPAC, Arena, and Machine Repair Simulation models. The study concludes that Machine Repair model is affordable for mines needing to estimate project truck requirements (Krause and Musingwini, 2007).

The paper by O’Connell and Sturgul (2010) studied the optimum size of the stockpiles at the Millerton Coal Mine (New Zealand). They used GPSS/H for the simulation and Proof Professional for the animation. The investigations recommended selective mining for future studies and answered many ‘what-if?’ scenarios. This was one of the largest simulation models developed for the surface mining operations.

Tarshizi (2012) developed a simulation and animation model for Fabero coal mine located in Spain. He used GPSS/H language and linked it with PROOF animation to analyze the performance of trucks and shovels. The study showed that the simulation is a useful technique to optimize the mine operations and answer many ‘what-if’ questions.

A correctly modelled haulage system always requires a detailed and microscopic analysis of the traffic behaviour. In this regard, Jaoua, Riopel and Gamache (2012) presented a traffic simulation framework for the classical discrete event simulation model of surface mines. The study described a methodology to accurately emulate the complex traffic behaviour of congestion or bunching. One of the other works on this subject is by Anani and Awuah-Offei (2013), in which they presented a methodology to account for truck bunching due to slow trucks and tested the cycle time dependency using Arena.

One of the recent works on data driven modelling and simulation framework is by Meng et al (2013). They developed a data driven model and simulation framework for the material handling systems of coal mines using Unified Modelling Language (UML), Petri, and Arena. This approach automatically generates discrete event simulation models, and is flexible to handle the later changes of material handling systems and operational data.

South African mines use real time transport tracking and scheduling systems. Simulation techniques gained importance in the country in order to explore the impacts of capital investments and mining methods. One such example is the Ingwe Douglas Pillar Project where simulation determined the combinations of trucks and shovels for a certain mining operation (Salama, Greberg & Schunnesson, 2014). Some other applications can be seen in Middleburg with shovel-truck simulation in an open pit mine, and Impala Platinum surface rail transportation simulating the ore flow from twelve shafts to two plant areas (Tarshizi, 2012). The mines also used simulation technology to optimize the long term supply of coal from mines to fuel operations. Sasol coal mines implemented it for the design, implementation of transport and storage, and blending operations (Harmse & Janse Van Rensburg, 2007).

Recently the mining industry has also given some attention to Google Earth based Mining Simulation System (GEMISIMS). It utilizes Google Earth COM API, Keyhole Markup Language (KML), a least-cost path algorithm, and GPSS/H simulation language. GEMISIMS simulation software determines optimum haulage paths for trucks, simulation and optimization of the number of trucks, and animation of the truck's travel by using the 3D render window of Google Earth (Choi et al, 2011).

Presently, mine models using standard mining software such as Vulcan and Datamine show the mine as a static 3D representation. In future it is likely that the users will view the simulation results in 3D animated graphics. It is expected that the internet will also play a major role in the future of mine system simulations (Sturgul and Li, 1997). The mine simulation industry will introduce web-based simulation models, and the combination of virtual reality with simulation and animation models will become part of mining simulations (Tarshizi, 2012).

2.3 Simulation Tools

Computer hardware and software technologies have seen considerable advancements in the last 50 years. The improvements are evident in the execution times, data storage capacity, object oriented design and programming, graphical interface and visualization etc. These improvements have also influenced the simulation software industry in that they provide faster processing, higher quality, better flexibility and user friendly packages (Sturgul and Li, 1997).

Most of the early simulation models used FORTRAN, which can be regarded as more of a research and methodology oriented language. In the late 1980s, the implementation technology of systems simulation made significant improvements, and the simulation applications became more oriented to problem-solving (Sturgul and Li, 1997). Now various tools are available for simulation purpose that can be divided in four categories: general purpose languages, simulation languages, general purpose simulation software packages, and mining software packages (Greberg and Sundqvist, 2011). Examples of *general purpose languages* are C++ and VBA. The *simulation languages* such as SIMAN, SLAM and GPSS are

object oriented discrete system simulation languages. The first two categories offer high flexibility but require good programming skills from the user. The *general purpose simulation software packages* (Simul8, AutoMod, ProModel, ARENA, Witness and Simio etc) require less programming skills but are less flexible as compared to the languages. *Mining software packages* such as SimMine are tailor-made software packages specifically designed for mining (Greberg and Sundqvist, 2011). Generally this category does not require any coding skills.

Lately the software industry has also created specialized animation languages to be used with the specialized simulation languages (Konyukh, Galiyev and Li, 1999). There are three types of graphics applications in relation to simulation packages. *Post simulation* or *playback animation* is, to a larger extent, independent of the simulation execution. *Concurrent animation* is one that occurs with the running of simulation. And, the *graphical model building* requires no program or programming (Sturgul and Li, 1997).

The simulation industry regards SIMAN as the first major simulation language that is capable of performing both discrete event and continuous simulation. CINEMA is the upgraded version of SIMAN with the addition of animation. ARENA added a graphical interface to this family of simulation and animation package to facilitate data analysis and model development (Sturgul and Li, 1997). Simtech introduced Arena mining simulation templates which offer a special package for mine system simulations. The templates save time by rebuilding similar simulation projects with the same model logic but having different parameters (Tarshizi, 2012).

SLAMSYSTEM, a microcomputer version of SLAM, is the first simulation language with graphical model building capability supported by the Windows platform. The other version of this family is AweSim which includes C-based simulation engine, external database connectivity, and extendibility by C or VBA (Sturgul and Li, 1997). SLAM II is capable of supporting discrete, continuous, network, and combined modelling (Castillo and Cochran, 1987).

Geoffrey Gordon originally developed GPSS for IBM in the early sixties (Ståhl et al, 2011; Sturgul, 2000). It is a classical general purpose simulation language that is widely tested and tried at commercial and academic level (Crain, 1997). The PROOF animation links with GPSS which makes it the most commonly used simulation tool in the mining industry (Sturgul and Li, 1997) that is still true. GPSS was continuously improved over years in terms of flexibility and execution time (Sturgul, 2000). Various versions emerged during its development phase, which include GPSS/360, GPSS/H, GPSS/PC, GPSS World, microGPSS, WebGPSS, WinGPSS and aGPSS.

Wolverine Software first introduced GPSS/H in 1970, and General Motors Manufacturing Development received its first commercial installation (Wolverine Software, n.d.). The next version of GPSS/H is SLX which provides layered architecture with powerful extensibility mechanisms. One major difference between GPSS/H and SLX is that GPSS/H is a flat and very large language, while SLX is deeper with a smaller number of constructs (Ståhl et al, 2011).

2.4 Conclusion

During last 50 years, computer technology has gained importance and received continuous improvements. Gradually it has become more user-friendly, and computing power has turned into mobile technology rather than remaining trapped in main-frames. Simulation software techniques have also improved with the advancements of computer hardware and software. The reduced computing costs and better computational performances transformed it into an ever growing industry, where simulation is widely used to analyse many real-world systems. Now there are a wide variety of computer systems available to best suit the requirements of simulation. The early simulations utilized costly and time consuming programming using procedural languages e.g. FORTRAN. The more recent development of general purpose simulation languages (e.g. GPSS) brought improvements; however, these generally focused on case-specific models. Presently the developer is not required to write long codes for small tasks, wait for long processing times, be concerned with storage capacities, or face difficulties in

code debugging. The simulation developer also has many software types to choose from depending on the requirements of the simulation exercise.

CHAPTER 3

TRUCK HAULAGE SYSTEM

3.1 Chapter Overview

The truck haulage system functions in an open pit mine in a non-stationary, unpredictable and outdoor environment (Jaoua, Riopel and Gamache, 2012). The ore and waste move from various loading locations to the dump sites through a network of haul roads (Bauer and Calder, 1973), and various parameters affect the system's performance. Modern mines also require a large fleet of equipment consisting of loaders, excavators, haulers and auxiliary machines etc.

This chapter evaluates the load-haul-dump cycle of an open pit haulage system, and discusses the relevant considerations and complexities of the haulage system.

3.2 Load-Haul-Dump Cycle

The key to successful operations in open pit mines depends significantly on proper equipment utilization. To achieve this, researchers had placed much emphasis on the study and improvements of loader-hauler operations (Brake and Chatterjee, 1979). It is thus imperative to examine the complete operational cycle to obtain meaningful and accurate answers (Deshmukh, 1970; Krause, 2006). Figure 3.1 shows a typical load-haul-dump cycle of the truck haulage system.

The hauler takes guidance from the characteristics or nature of the system and operates in the cycle in following manner (Bauer and Calder, 1973): -

- The hauler arrives at the loader. If the loader is free it proceeds to the loading position, otherwise it joins the queue on First-In-First-Out (FIFO) basis. The single-side or double-side loading characteristic of the loader defines the loader-hauler interaction parameters. The loading time depends on various factors such as hauler payload and capacity, loader bucket size, number of bucket passes, material density, and positioning time etc.

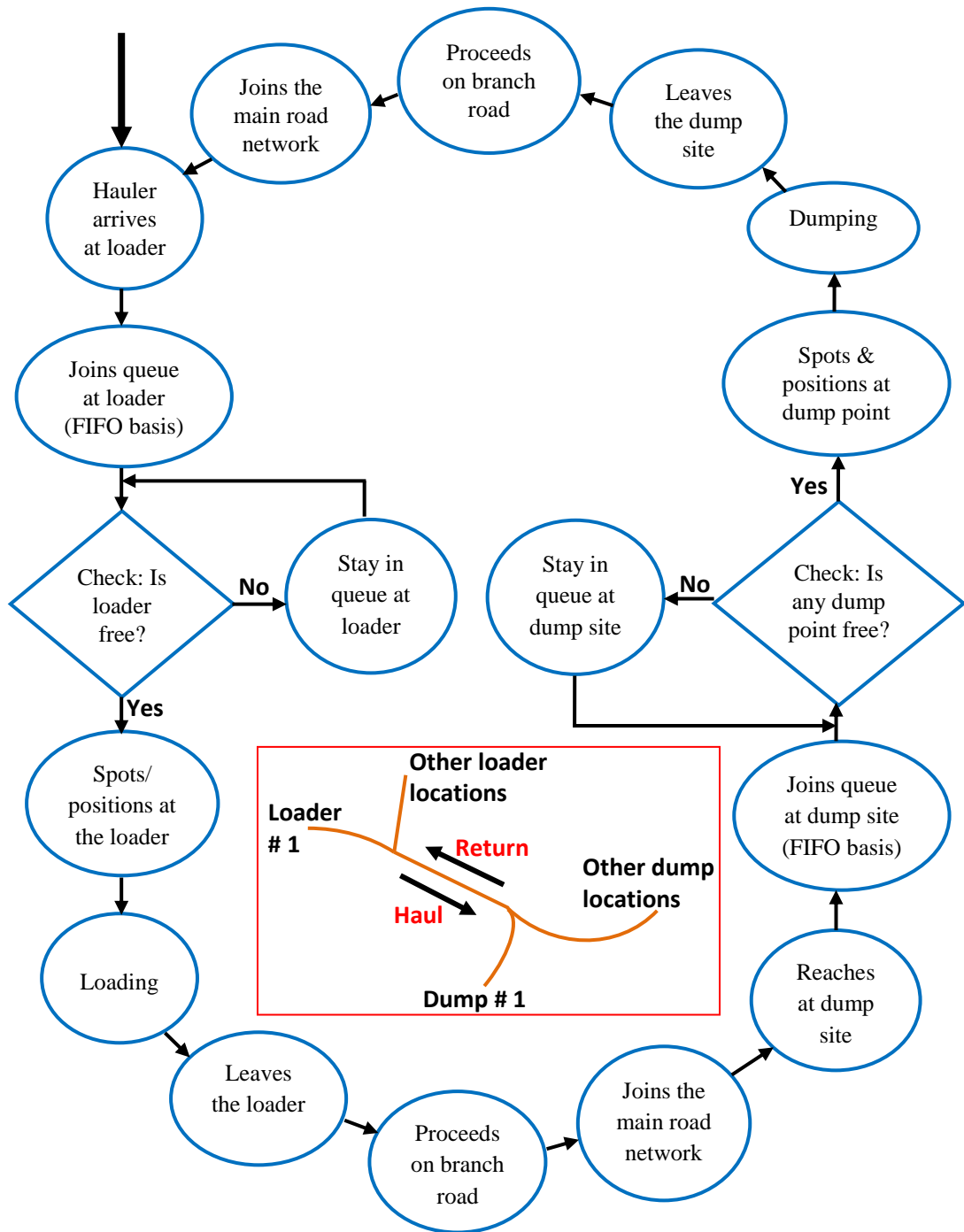


Figure 3.1: Load-haul-dump cycle

- The hauler leaves the loader, and proceeds on the branch road to join the main road network. The haul time depends on the profile of road sections (rolling resistance, grade-ability etc), mechanical characteristics of the hauler, and any restrictions imposed by the mine. Bunching of haulers and delays at the junctions also affect the haul time. Bunching occurs when a fast moving hauler

follows a slow moving hauler, and depends on the system characteristic to allow overtaking or not. Delay at a junction depends on the right-of-way and number of haulers already waiting at the junction.

- The hauler reaches one of the dump sites (crusher, waste dump, or stockpile). The allocation of a dump site can be on trip-to-trip basis or it can be for a complete shift. Within a dump site, there can be one or more dump points (or bays). The formation of a queue depends on number of available dump points and the number of already dumping haulers. The dump time comprises spotting and actual dumping.
- The hauler returns to one of the loaders depending on its allocation on a trip-to-trip or shift basis, and the cycle repeats itself.
- The other events which affect the cycle time include re-fuelling, lunch breaks, shift change, mechanical breakdowns, re-routing, and re-assignments. Besides, the operators' efficiency also contributes to overall performance of load-haul-dump cycle (Krause, 2006).

3.3 Considerations for Simulating Truck Haulage System

The aim is to achieve the effective utilization of all the equipment in the dynamic mine environment and this brings complexity to the system. For instance, the increase in number of haulers increases the loader productivity but it results in decrease of hauler productivity and may congest the system. The production by loader depends on the type and quality of material, and the size and numbers of haulers being loaded. The number of loads produced by haulers depends on the queuing conditions at the loader and dump locations, and the number and speed characteristics of other haulers operating in the mine (Bauer and Calder, 1973). The complexity of the system, interferences between the sub-systems, and the lack in management skills are the major bottlenecks (Zhang et al, 2006) in improving the system efficiency.

The efficiency of a load-haul-dump cycle depends on many interdependent and dynamically-changing variables that require proper analysis to develop a simulation model. In return, the accuracy of a simulation model depends on the

number and correctness of assumptions made on these variables. The significant considerations necessary in order to simulate truck haulage systems are summarized in the following paragraphs.

3.3.1 Uncertainty

Operations management in an open pit mine involves many uncertainties in the technical, economic and operating areas. The mining operation is dynamic in nature and generally faces considerable changes in the mine plan. To evaluate an ideal fleet selection, the primary parameters that are subject to variability are the hauler cycle time and availability of equipment. Hauler cycle time is considered more important in terms of its variability than the loader cycle time (Cebesoy, Gzen and Yahşi, 1995).

The simulation of a truck haulage system requires data that closely describes the real mine system. The input data is often difficult to collect due to variations in the operational parameters of the fleet and different managerial policies of the mines. It may affect the simulation results, as the correctness of a simulation model depends on proper representation of the source of randomness for the system. To accurately describe the system, it is therefore necessary to generate random observations throughout the production duration (Kolonja and Mutmansky, 1993).

Literature review shows considerable research in determining the probabilistic properties related to equipment cycle times. These works present a range of distributions types applicable for the haulage cycle variables (Krause, 2006). As an example, Czaplicki (2009) expresses that set of functions applicable for hauler loading times is quite rich, starting from exponential probability distribution, Weibull function, lognormal function, Erlang function, up to Gaussian function.

The determination of operating cost of the mining equipment is, in itself, a vital problem. Equipment operating expenditure in cost per ton is a function of productivity; productivity relies on availability; and availability depends on the

age of equipment (Christina, 2008). The reliability of equipment and efficiency of operators also vary from case to case basis.

One of the solutions to reduce uncertainty is the development of automated equipment in modern open pit mines. The automation has the potential to increase the equipment productivity and improve the safety standards (Zhang, Kinnane & Rogers, 1994).

3.3.2 Heterogeneous Fleet

In an open pit mine, different loader types may be operating at different locations. Similarly, the haulers operating between the loaders and dump sites may also have mixed types. The mixed fleets generally arise when newly purchased equipment joins the older fleet to meet the productivity targets (Christina, 2008). As the heterogeneity of a fleet increases, the model becomes more complex due to an increase in number and interdependencies of variables (Krause, 2006).

The hauler fleet is more likely to be heterogeneous, as increased numbers of haulers generally operate to meet production as compared to the small number of loaders (Christina, 2008). The mixed hauler types affect the simulation model by representing different travel speeds and payloads. This in turn may result in an increase in bunching and non-linear production output.

While modelling a heterogeneous fleet, the literature review considers “mutual exclusivity” as a common restriction. It allows only one type to be used. Cebesoy, Gzen and Yahşi (1995) explain heterogeneous fleets as unacceptable and unthinkable; however anecdotal evidence has supported this claim to date (Christina, 2008).

3.3.3 Multi-loader, Multi-dump Sites

The haulage system in open pit mines may represent a complicated model due to presence of multiple mining locations, multiple dump sites, or multiple haulage routes. These location differences can sometimes lead to the selection of a fleet that is incapable of meeting the production targets (Christina, 2008).

A single loader sending material to a single dump site through a single haul road is the simplest haulage system (Cross and Williamson, 1969) that a modeller can model with relative ease. The model becomes complex when one loader connects to several dump sites or when several loaders supply material to one dump site through a haul road network (one-to-many relationship). The complexity further increases when there are many-to-many relationships between various loaders and dump sites (Burt and Caccetta, 2014).

The operations management of the mine may task an individual loader to extract the ore or the waste from a location, or to perform ore blending. Moreover, the loader can also change its location during its operational duration. All the mentioned parameters demand special attention during the development of a simulation model.

3.3.4 Bunching of Haulers

Tracking the inherent traffic behaviour is an important aspect to correctly simulate a haulage system. It is more pronounced in the mining environment, where the mine policy often restricts the overtaking or bypassing of other vehicles. In any case, the behaviour of a hauler operating in an open pit mine can be significantly variable due to variations of its travel speeds, interaction with other en route haulers (Jaoua, Riopel and Gamache, 2012), and delays at road junctions.

Not only the characteristics of hauler and road but also the other haulers in the system affect the travel speed of the hauler. The more the number of haulers in the system, the greater is the chance of bunching or interference of haulers (Bauer and Calder, 1973). The junctions in the road network also increase the total travel time. The delay at junction depends on the stoppage time, delay due to right-of-way, and number of already present haulers at the junction.

Bunching increases the cycle time, fuel consumption and emissions, and reduces the utilization and productivity of equipment. Identifying the factors causing bunching are easy, but the actual challenge lies in the incorporation of these factors into the simulation model (Anani and Awuah-Offei, 2013).

Many previous studies did not adequately explore and model the bunching of haulers in mine road network (Anani and Awuah-Offei, 2013); often the models accounted it by incorporating a simple reducing factor (Christina, 2008). Amongst the exceptions are Kolonja and Mutmanský (1993), Jaoua, Riopel and Gamache (2012), and Anani and Awuah-Offei (2013), who have presented some noteworthy solutions by using simulation techniques. Most of the previous studies on mine simulations assumed that the data of statistical distributions is independent and identically distributed. However in the case of a truck haulage system, the hauler cycle time cannot remain independent due to haulers bunching behind the slow or stopped hauler (Anani and Awuah-Offei, 2013).

3.3.5 Hauler Dispatching

An efficient haulage system is able to provide a systematic and dynamic solution as to how the haulers will be assigned to the loaders (Li, 1990). The open pit haulage system functions through fixed or variable allocation. In fixed allocation, the haulers are locked in a fixed loader-dump route during the shift. This form of dispatching is cost-effective, simple and easy to implement as the decision is to be taken at the start of shift. However it is inefficient in production and does not cater for breakdowns. For instance, if a hauler breaks down during the shift, the loader remains under-utilized for its duration. In a different case, if a loader breaks down during the shift, the haulers assigned to it remain idle for the period (Wilke and Heck, 1982).

The variable allocation, on the other hand, dispatches the hauler to a destination as per the system state at the allocation time (Li, 1990). This involves employing a computer dispatch system which controls the routings of haulers via radio communication (Castillo and Cochran, 1987). The variable allocation is comparatively more efficient in improving the equipment utilization. At the same time, it is a costly solution and the benefits are highly dependent on data communication effectiveness, processing speed, haulage network configuration, fleet size and the use of specific dispatch policy (Zhang, Kinnane & Rogers, 1994). The most commonly used variable allocation policies are: minimize loader production requirements, minimize hauler waiting time (or maximize hauler use)

and minimize loader wait time (or maximize loader use) (Bonates and Lizotte, 1988; Castillo & Cochran, 1987; Çetin, 2004). Some of the other policies that may be implemented include: minimize hauler cycle time, minimize loader saturation, earliest loading loader, and longest waiting loader (Çetin, 2004; Kolonja and Mutmanský 1993). The selection of the best dispatching policy is a site specific problem, especially where grade considerations and production targets exist.

This research implements the variable allocation policy of *Minimize Production Requirements* (MPR) in the simulation model. The aim of this policy is to achieve the target productions of the loaders and the dump sites that have been optimized by a linear programming method or any other approach (Kolonja and Mutmanský, 1993). The policy allocates the hauler to a location which is most behind its production schedule while taking into account the total capacity of the en-route haulers. It is similar to the policy of minimising loader production requirements, with the difference that it also dispatches the hauler to the most lagging crusher or waste dump. The research also considers the assignment to the dump sites because the research is focusing on multi-loader multi dump sites. This policy is most suitable for the mines with strict quality control objectives. It can dispatch several haulers in succession to the same location that is lagging in production due to an earlier breakdown, which may cause queuing at the location. This might be desired if a given target production is strictly required for blending or any other purpose. However, it would result in sacrificing the total system production (Çetin, 2004).

A simulation model for dispatching is more complex as compared to the one for design. It demands the reflection of real time process, taking into account during-the-process-changes and making predictions (Konyukh, Galiyev and Li, 1999). Software such as DISPATCH is commercially available to handle variable allocation problems. It works on linear programming and heuristic methods targeted to achieve the desired dump rate and blend quality (Meng et al, 2013).

CHAPTER 4

DESIGN METHODOLOGY OF THE SOFTWARE PROGRAM

4.1 Chapter Overview

This chapter explains the design and development methodology of the simulation software program. The software program works under the guidelines of a design concept and focuses on the arrangement of data in a logical and mathematical manner. It utilizes an animated simulation model which represents an open pit mine in the working conditions. The simulation model uses actual or planned statistical data of the real mine, and the animation shows the mine functions in cartoon fashion (or moving symbols). The visual interface communicates with user for obtaining the inputs and showing the outputs.

After fine tuning, the software program should be capable of answering many mine design and optimization questions. Examples are: what will be the production or economic benefits, if one more hauler is added in the fleet, or if a larger hauler is replaced by a smaller hauler, or if a smaller loader is used, or if the length of haulage road is increased; and when is the right time to add a new hauler or loader etc?

4.2 Selection of Tools

To perform the mine simulation of a truck haulage system, one has to select a simulation package. The selection criteria of a simulation package generally depend on multiple factors. The most significant factors include: ease of use, debugging and troubleshooting, ability to import and export data, compatibility with other software, and the ability to produce desired outputs (Yuriy, 2005).

After analysing various options, this research project used GPSS for simulation, along with PROOF for animation. In addition, the research made use of VBA to develop a user friendly interface for the Windows operating system.

4.2.1 GPSS

GPSS (General Purpose Simulation System) is a programming language for discrete event simulation. Various industries have utilized it to develop simulation models of their operations, e.g. traffic patterns, manufacturing environment etc. IBM originally developed it for the mainframes. Later on it was transformed into three main families, for which support and development have continued, namely: GPSS/H, GPSS/World, and the educational aGPSS systems family (Ståhl et al, 2011).

GPSS/H is the version of GPSS developed by James O. Henriksen (which explains the H). It is a low level nonprocedural language that can be regarded as both a computer language and a program (Sturgul, 2000). It functions as a Windows console-mode application and is launched from a command line. Wolverine Software maintains and supports GPSS/H. This research uses the laboratory license of GPSS/H which was acquired from Wolverine Software.

Other simulation languages may also provide proper solutions, but this research selected GPSS/H due to following advantages (O'Connell and Sturgul, 2010; Sturgul, 2000):-

- Continuously being upgraded since 1961.
- Widely available.
- Fast due to use of machine language.
- Flexible and a wide variety of problems can be solved.
- Good literature is available for study and training.
- Successfully used for simulation of some of the largest models.

4.2.2 PROOF

PROOF is a program similar to CAD that graphically represents the simulation coding and calculations (O'Connell and Sturgul, 2010). It provides a simple yet powerful set of commands for simulation models to display the animations. It has been in use for mine simulation and animation for a long time (Tarshizi, 2012).

In 2001, Wolverine Software introduced two new versions of the PROOF animation software family; namely PROOF5 – a 2D animator, and PROOF3D (Ståhl et al, 2011). In the last decade, the software company has upgraded these versions regularly. This research makes use of PROOF5 (P5) to develop the 2-dimensional animations of the simulation. Wolverine Software provided the laboratory version of P5 along with GPSS/H.

P5 is not directly linked with GPSS/H, and other simulation languages can also use it. It provides flexibility to generate concurrent or post simulation animation, and is dependent on the user for the levels of detail required in the animation. Though P5 provides the built-in drawing tools for creating the system layouts, the user can also import the layout data with the simulation details.

4.2.3 VBA

VBA (Visual Basic for Applications) is an implementation of Microsoft's event driven programming language that is designed to operate using the Windows operating system. This research makes use of version 2008 of VBA, downloaded from www.microsoft.com.

The purpose of this language is to build a Graphical User Interface (GUI) between the user and the simulation package. The front-end-dialogue makes it easy for the user to define the input parameters and graphically illustrate the mine layout. The VBA platform also displays the outputs generated by the simulation in an organized manner. In the developed software program, VBA handles the communication from/ between GPSS/H and P5. It exports data to GPSS/H and P5 in the required format, after which the simulation and animation process can start. It also imports data from GPSS/H to show the results to the user.

4.3 Design Concept of the Software Program

Before developing any simulation software program, it is necessary to establish a design concept. The design concept establishes a conceptual architecture for the development and working of the software program. The software program takes guidance from this architecture for its desired functioning.

This research initially developed a basic model for a simple truck haulage system, and implemented fixed hauler allocation. It helped in understanding the working and study of the simulation language GPSS/H. It also confirmed the modelling effort and served as a framework to develop an information gathering structure in VBA. Later on the model included the complexities of a heterogeneous fleet, multi-loader multi dump sites, bunching of haulers, and variable allocation. The software program utilized the P5 animation to verify the simulation process.

Appendix C contains the simulation code written in the GPSS/H language. Appendix D includes the electronic version of the simulation program on a CD, along with a brief on how to use the CD. The CD contains the installation and video files in two separate folders, where the video files demonstrate various case studies (which are discussed in chapter 6).

4.3.1 Information Flow Architecture

Figure 4.1 depicts the overall design concept of the simulation software program, and illustrates the information flow architecture between VBA, GPSS/H and P5. The blue box shows the environment or domain of VBA, red is for GPSS/H, and green for P5. The two yellow outlined boxes encompass the inputs and outputs shown to the user; all other processes work in the background.

VBA acts as the in-charge program to control the overall process, as it not only manages the communication with the user but also with GPSS/H and P5. The user provides all the input data (statistical and graphical) in the user friendly GUI of VBA. It performs preliminary calculations and manages the data in an appropriate form. It also saves it in a backup file so that user may access it at later stages.

After converting the data into pre-defined formats, VBA writes it in two separate files. One file contains the input data sets required by GPSS/H (with file extension of GPS), and the other contains the mine layout graphical data (LAY file) required by P5. On the user's command, it then calls the GPSS/H program.

GPSS/H accesses its input data sets and runs the simulation model. The simulation model simulates the truck haulage system within the specified

boundary conditions and using the given assumptions. The input data sets received from VBA provide the basis of simulation, as the procedures written in GPSS/H program are variable driven. After successful completion of the simulation, GPSS/H writes the outputs in two files. The first output file contains the simulation results such as total entries at loaders and dump sites, average queue contents etc. VBA accesses this output data generated by GPSS/H, and then displays it in an organized manner to the user. VBA also carries out some of the post simulation calculations to present the comprehensive results. The second output file generated by GPSS/H contains the commands for animation (ATF file). The ATF file carries precise information about the actions of each simulated entity with reference to the simulation time.

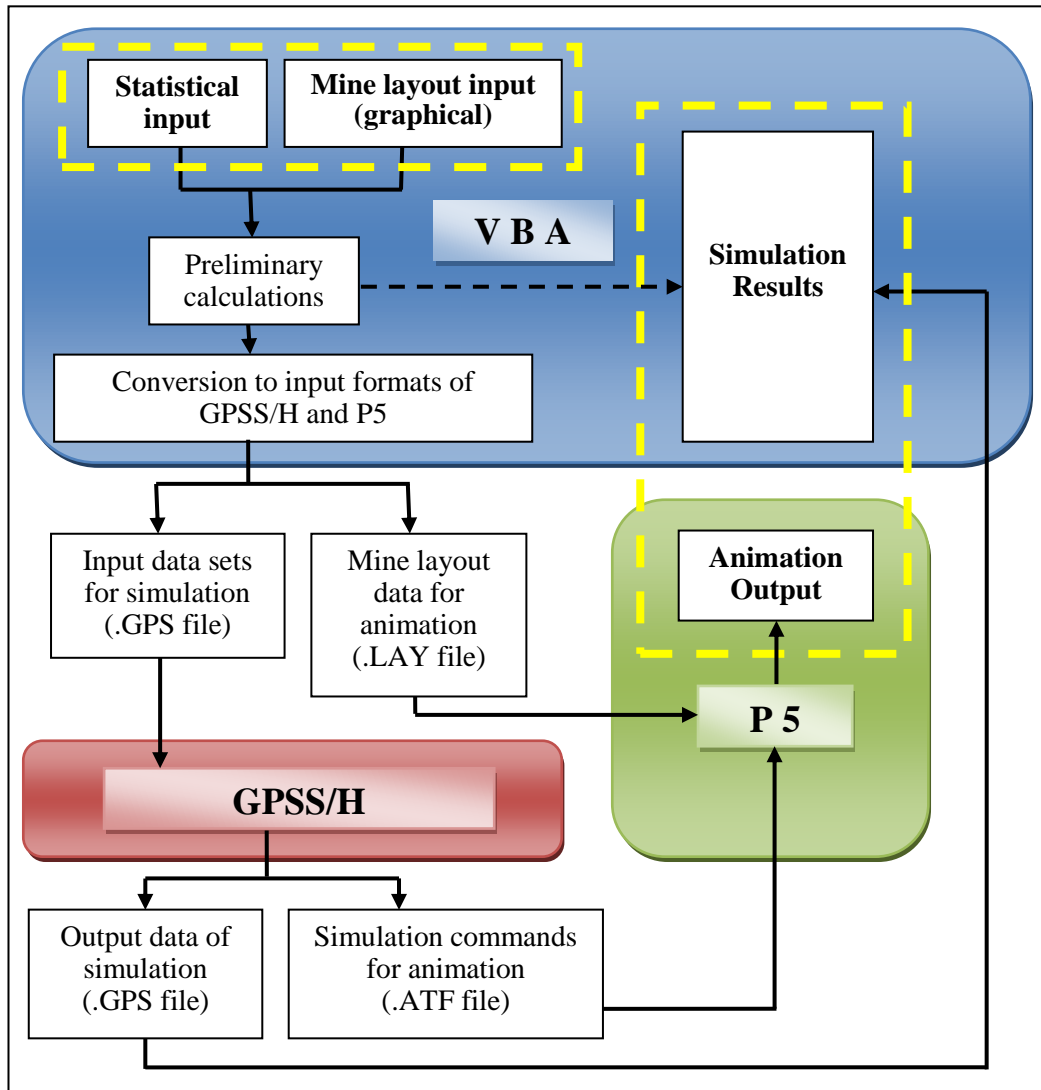


Figure 4.1: Information flow architecture

If user wants to see the animation, VBA calls upon the P5 software. The P5 software accesses the LAY file generated by VBA and the ATF file generated by GPSS/H, and then runs the animation. The user views the animation in the P5 environment, and can at any time switch back to the GUI of VBA.

4.3.2 Assumptions and Constraints

To simulate the open pit haulage system, the research makes following basic modelling assumptions: -

- The model performs a continuous simulation for the number of shifts desired by the user i.e. without any rest for the shift breaks.
- Auxiliary transport which may be operating in the mine is not modelled.
- All junctions in the road network have stop signs with a FIFO discipline.
- Haulers are not allowed to overtake each other in the mine road network.
- Loaders do not change their locations during the period of simulation.
- All loaders perform single side loading.
- Loaders and dump sites are specific to ore or waste only. The model does not handle ore blending at the loaders or dump sites.
- At the simulation start, haulers are empty and parked in the parking area.
- When a dump site is unavailable, the hauler cannot use any of its dump points.
- For variable allocation, the dispatcher makes the new assignment at the exit from the loader and the dump site. If the assigned location becomes unavailable after the assignment, re-routing is not done for that particular hauler.
- If a loader fails or made unavailable during the loading of a hauler, the hauler waits for the loader to be made available again to complete its leftover loading. On the other hand, if a dump site fails or is made unavailable during unloading of a hauler, the hauler completes its unloading and leaves the site.
- The simulation model uses a normal distribution for all the random variables except the breakdowns. It uses an exponential distribution for the breakdowns of loaders, haulers, and the dump sites.

- The time studies and user defined operating and non-operating delays per shift take into account the following timings or delays: -
 - The acceleration and de-acceleration of haulers.
 - Haulers travel time from the parking area to the loaders at the start of shift, and from their final locations to the parking area at the end of each shift.
 - The re-fuelling and lunch break delays, if held during the shifts.
 - Blasting and cleanup times at the loaders (MTTR of the loaders can also symbolize blasting and cleanup delays, if the overall loader operation allows such representation).

The simulation software program is applicable for short to medium term planning, and can handle medium to high complexities of the system. It imposes the following constraints or limitations for using the software program: -

- Maximum number of loaders: 10 (with 10 different types)
- Maximum number of haulers: 60 (with 10 different types)
- Maximum number of crushers: 5
- Maximum number of waste dumps: 5
- Maximum number of road sections in the mine: 50
- Maximum number of road sections in any single route: 10
- Maximum length of each road section: 15 km
- The software program asks the user to manually enter the operational parameters of the equipment after consulting the OEM specifications and carrying out field investigations. The manufacturer's database of haulers and loaders is not linked with the software program.
- The input from the graphically illustrated mine layout permits one possible route between two locations. Remaining within this constraint, the software program allows connecting multi-loaders with multi-dump sites.

4.4 User Inputs

The reliability of results produced from the simulation program is a function of the accuracy of collected input data. The performance of a simulator is only as

good as the input data it receives. These inputs comprise the equipment manufacturer's specifications supplemented by field study data. Every mine is different in fleet size and type, number of crushers and waste dumps, road network, and operational policies etc. It demands separate time studies for every mine under consideration without any generalization of data. The time study operation requires clear recognition of each individual event, and thereafter the identification of outliers (Çetin, 2004). After completing a time study operation, the user checks it for fitness by comparing it to a probability distribution.

Table 4.1 presents the input parameters that a user provides in numerical form. The program categorizes these inputs into six major categories namely: project basics, roster and time delays, hauler, loader, mine layout and parameters, and number of shifts to be simulated. The program offers 'number of shifts to be simulated' as a separate category to allow the user to quickly view the outputs with a varying number of shifts.

In the roster and time delays category, the non-operating delays per shift apply to those events in the shift during which the equipment's engine is switched OFF. Examples are meal breaks, weather delays and pre-shift service etc. On the other hand, the operating delays per shift are the conditions when the engine is ON but the equipment is not operating in its designated haulage cycle. For this research, the applicable examples are re-fuelling, hauler's travel from the parking area to its loaders at the start of shifts, and to the parking area at the end of shifts. Any secondary task assigned to the equipment other than haulage cycle also makes it an operating delay. In the simulation model, the waiting times of hauler or loader and the equipment breakdowns are not taken as operating or non-operating delays. The model handles these delays during the simulation. Figure 4.2 explains the distribution of the times during a shift.

The user defines the haul road geometry in the mine layout and parameters section. The essential input parameters comprise of length and curve angle of the road sections, and the speeds of each hauler type – both for loaded and empty conditions. These speeds are the rim-pull curve velocities of the haulers further supplemented by field investigations. The user obtains the rim-pull velocities

from the manufacturer's specifications by applying the road characteristics (grade-ability, rolling resistance) and hauler gross vehicle weight. Figure 4.3 shows a screenshot of the mine layout and parameters section (example).

Table 4.1: Input parameters for the software program

1. Project Basics	4. Loader
- Desired ore production per year	- Total number of types in mine
- Waste production per year *	- For each loader type
- Currency unit – e.g. ZAR, USD	- Manufacture *
- Overall stripping ratio (OSR)	- Class *
- Ore bank density	- Model *
- Waste bank density	- Number of units in mine
- Ore loose density	- Maximum load in each bucket (tons)
- Waste loose density	- Capacity (m ³)
2. Roster and Time Delays	- Bucket fill factor (%)
- Hours per shift	- Time for 1 st bucket pass
- Shifts per day	- Time for each subsequent pass
- Standard delays	- Hauler exchange time at the loader
- Non-operating delays per shift	- Cost per operating hour
- Operating delays per shift	5. Mine Layout & Parameters
- Scheduled lost shifts per year	- Overall size of mine
- Unscheduled lost shifts per year	- Number of crushers
- Maintenance shifts per year	- Number of waste dumps
- Operational delays	- Maximum speed limit on site
- MTBF & MTTR for loaders	- At crushers
- MTBF & MTTR for haulers	- Hauler spot time
- MTBF & MTTR for crushers	- Hauler dump time
- MTBF & MTTR for waste dumps	- At waste dumps
- Delay at road junctions	- Hauler spot time
- Operator combined proficiency (%)	- Hauler dump time
3. Hauler	- Haul road geometry (for each road section)
- Total number of types in mine	- Number (ID) of road section *
- For each hauler type	- Title of road section *
- Manufacture *	- Length
- Class *	- Curve angle (if road section is curved)
- Model *	- Grade-ability % *
- Number of units in mine	- Rolling resistance % *
- Payload (tons)	- Speed for each hauler type (loaded)
- Capacity (m ³)	- Speed for each hauler type (empty)
- Top speed (loaded)	6. Number of shifts to be simulated
- Top speed (empty)	- Number of shifts
- Cost per operating hour	

* *Optional parameters*

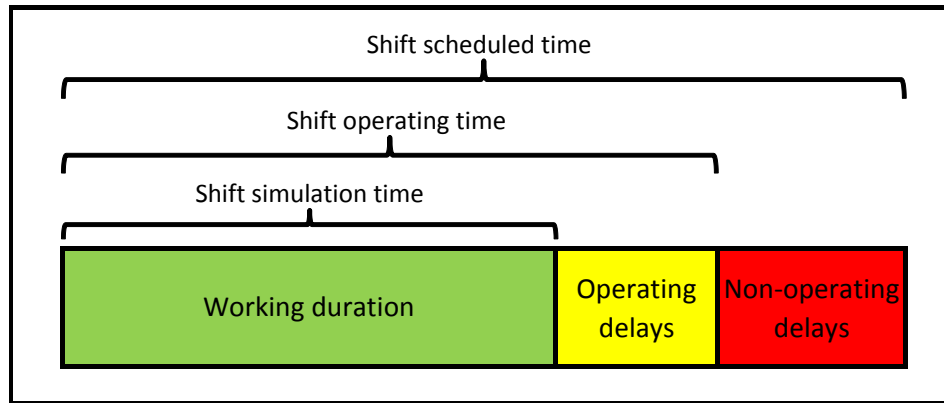


Figure 4.2: Distribution of the times during a shift

Basic Parameters - Mine Layout (C:\project\1_complete_7)

Overall Size of Mine: 3000 m X 3000 m

No of Crushers: 2

No of Waste Dumps: 1

Max Speed Limit on Site: 55 km/hr

Information

- ☒ Essential for Mine Layout
- ☐ Essential for Simulation
- ☐ For Record Purpose Only

In Waste Dump Area

Hauler Spot Time: 00:40 mm:ss

Hauler Dump Time: 04:20 mm:ss

In Crusher Location

Hauler Spot Time: 00:40 mm:ss

Hauler Dump Time: 04:20 mm:ss

Haul Road Geometry

No	Title	Length (m)	Curve Angle	Grade%	RR%	*SL-HT 1	*SE-HT 1	SL-HT 2	SE-HT 2
1	pit bottom	150				40	50	60	70
2	uphill ramp 1	410				h	h	h	h
3	uphill ramp 2	1090				45	50	50	55
4	bench 6	300	-90			30	35	40	45
5	crusher haul r...	2500	-180			35	40	45	50
6	dump 2 haul r...	600				H	H	H	H
7	2nd crusher r...	250				40	45	50	55
8	link road	1090				25	30	35	40
*									

*SL-HT1: Speed (km/h) loaded for hauler type1; *SE-HT1: Speed (km/h) empty for hauler type1 ('H': hauler max. speed)

Figure 4.3: Screenshot of inputs - mine layout and parameters (example)

In the graphical input section, the user explains the mine layout graphically. Here, the user connects the already defined road sections, and places the dump sites and loaders on the network. The user also provides information about the material type at each loader (i.e. ore or waste), number of dump points at each dump site, and desired percentage production contributions of each location. The simulation model uses this data primarily for the MPR (Minimize Production Requirement)

variable allocation. For fixed hauler allocation, the user assigns each hauler in a sequence to its loading and unloading locations. The program automatically computes and displays the connecting road sections. Figure 4.4 shows an example of the graphical input section.

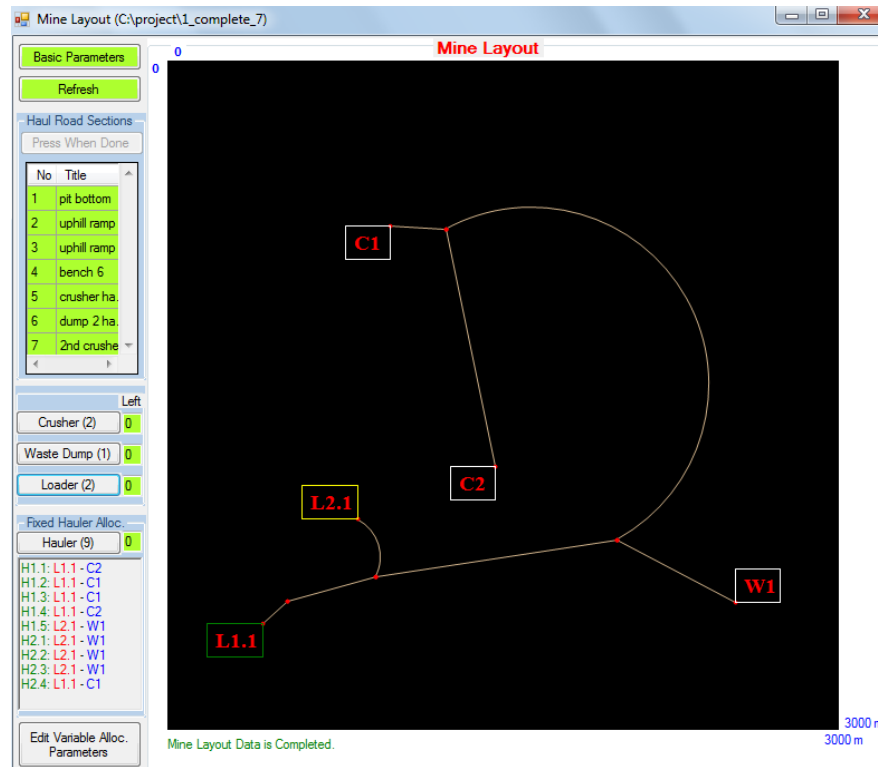


Figure 4.4: Screenshot of graphical input for mine layout (example)

4.5 Outputs of the Software Program

The software program receives the simulation results from GPSS/H. After performing post-simulation calculations, it displays the outputs to the user. Figure 4.5 shows a screenshot of an example displaying outputs of a fixed allocation system. The following is a summary of the outputs:-

- With reference to ore and waste (separately)
 - Number of loaders, haulers, and dump sites used
 - Desired production per year
 - Target production for the simulated duration
 - Achieved production during the simulated duration
 - TPOH

- With reference to overall production in mine (ore and waste combined)
 - Total TPOH
 - Total CPOH
 - Total CPT

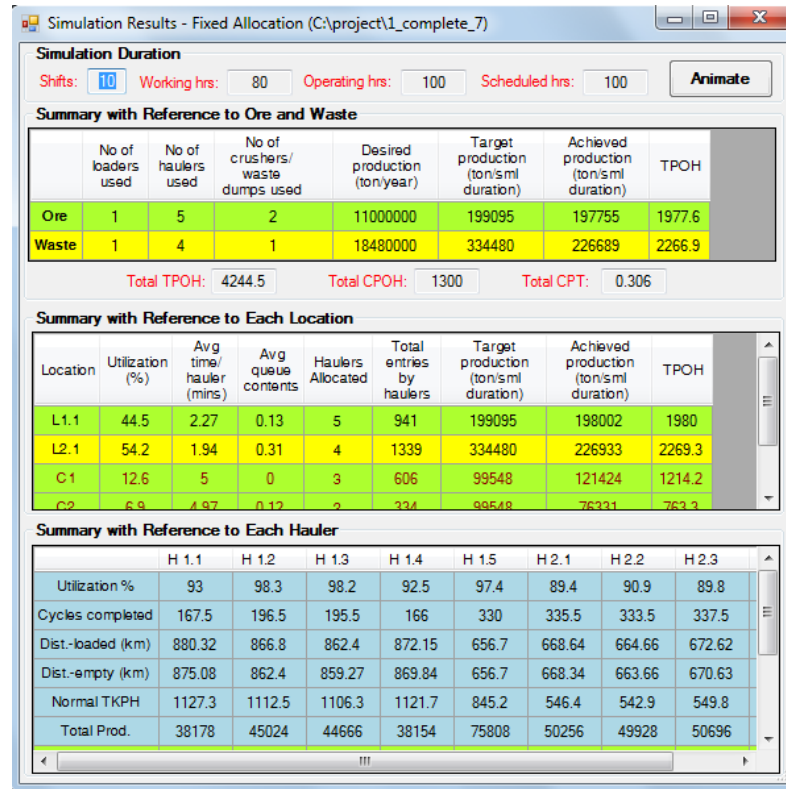


Figure 4.5: Screenshot displaying the simulation results (example)

- With reference to each loader, crusher, and waste dump
 - Percentage utilization
 - Average time per hauler
 - Average queue contents
 - Number of haulers allocated (in case of fixed allocation)
 - Total entries by haulers
 - Target production for the simulated duration
 - Achieved production during the simulated duration
 - TPOH
- With reference to each hauler
 - Percentage utilization

- Total number of cycles completed
- Total distance travelled - with load
- Total distance travelled – empty
- Normal TKPH
- Total production delivered at the dump sites
- Distribution of productions received and delivered at each location

If the user desires to view the animation of a mine haulage system, the program transfers control to the P5 software. The animation displays the working of system with the help of coloured symbols along with relevant details and graphs. The user can jump to any instant of simulation time for viewing the updated system status. Figure 4.6 shows a screenshot of an example displaying an animation in progress.

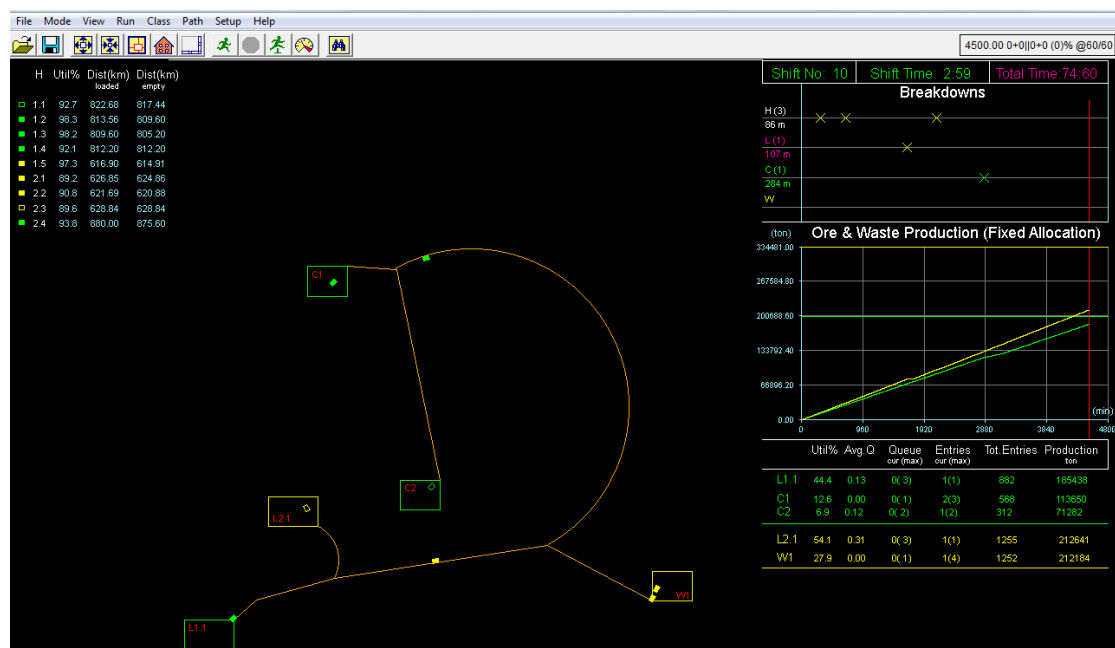


Figure 4.6: Screen shot of animation (example)

4.6 Conclusion

The developed simulation program combines the strengths of the three software programs i.e. VBA, GPSS/H, and P5. The research uses the first software program for developing the GUI, second for the simulation model, and third for demonstrating the animation. The design architecture of the simulation program

relies on the effective integration and communication between these three software programs.

The accuracy of the time studies performed in the field and determination of correct operating and non-operating delays per shift are the vital factors to produce confident simulation results. The significant assumption of the simulation program is the implementation of normal distributions for all the haulage activities, and exponential distributions for the breakdowns. It demands that the user carries out correct interpretation of the results produced by the simulation program.

CHAPTER 5

FUNCTIONAL METHODOLOGY OF THE SIMULATION MODEL

5.1 Chapter Overview

The simulation of a real system requires a mathematical model. The mathematical model defines a set of rules that governs the interaction of the various entities of the system. It allows the user to compare various operations by altering the rules of the respective operations. The program then applies the new rules of the model, and allows the entities to interact with each other (Cross and Williamson, 1969).

This chapter discusses the functional methodology of the simulation model. It illustrates how the user inputs transform into the pre-arranged data sets (matrices) which drive the simulation model. This chapter also discusses the sub-model structures that handle the concerns of system randomness, heterogeneity, multi locations, bunching, and dispatching. In the last, it explains the output data sets that the simulation model manages in order to generate the desired results.

5.2 Simulation Model Overview

The developed simulation model replicates the activities of the mine fleet during the operational shifts. It makes use of following assumptions in the simulation language to represent the real system: -

- Transactions – Haulers.
- Facilities – Loaders (traffic management also utilizes the concept of facilities).
- Storages – Dump sites.
- Queue time – Waiting time.
- Service discipline – FIFO (First-In-First-Out).

The simulation model is stochastic. It uses probability distributions to generate the loads, times for the sections of load-haul-dump cycle and the unavailability of the equipment or locations. When a transaction seizes a facility, it becomes unavailable to other transactions for the duration of its service time. The storage is

similar to a facility; however its capacity to serve a number of transactions may vary. This form of simulation accurately models the queuing of transactions at the facility and storage sites, and eliminates the need of separate calculations.

The model initializes the system by assigning the empty haulers to the loaders following a fixed or variable allocation policy. When a hauler arrives at the loader, the model represents it by a transaction arriving at the facility. There it can face one of two possibilities. If the facility is free, it seizes the facility directly; in the other case it stays in the queue and waits its turn. The transaction releases the facility after the elapse of service time. The model picks up the service time for the particular facility-transaction match from a matrix. This matrix contains the service times of all the possible combinations of facilities and transactions. Here, the model also updates its output data sets of the number of transactions served and tonnage loaded by the facility.

After the release of transaction from the facility, the simulation clock advances in increments equalling travel times taken on each road section. This simulates the hauler travelling on the route assigned through fixed or variable allocation. The model calculates the travel time increments for each road section from the allowable speed and length of the road section. The allowable speed on each road section comes either from the hauler rimpull curve velocity (dependent on the haul road specification and hauler gross vehicle weight) or the mine speed policy. During the process of advancing the travel time increments, the model ensures that the particular transaction does not occupy the same physical space currently under use by another transaction. This may increase the travel time by keeping the haulers at a safe distance apart and disallowing overtaking (bunching of haulers explained in section 5.4.2). A junction present in the road network also serves as facility, where the transactions seize and then release it one at a time. When a hauler reaches a junction, it follows the FIFO discipline.

When a hauler reaches the dump site, the model represents it by a transaction reaching the storage. If the storage is occupied to its full capacity or is unavailable, the transaction waits in the queue; otherwise it enters the storage. The storage sends the transaction to one of its storage spaces (representing dump

points) for the time equal to the dumping time. The total dumping time is the sum of actual dumping time and spotting time. Here, the model updates the output data sets of the transactions served and the load received by the storage. After elapse of dumping time, the transaction leaves the storage and follows the return route.

The simulation model can run for a number of consecutive shifts for more detailed analysis of the production parameters. During the simulation run, the model keeps a log of all the events with reference to the simulation time, and saves it in a separate ATF file. After successful completion of a simulation, this ATF file serves to show the post simulation animation to the user. The model also sends a summarized output report to the program at the end of simulation.

5.3 Input Data Sets for the Simulation Model

Visual Basic for Application (VBA) sends the pre-arranged input data sets to the simulation model. Table 5.1 shows these input data sets which take the form of 1-D and 2-D matrices. During preliminary calculations, VBA allocates ID numbers to all the haulers, loaders, dump sites, junctions, uphill paths, and downhill paths. It then arranges the matrices in a sequence, with the rows of each 2-D matrix following a pattern of ID numbers. GPSS/H uses the same ID numbers for referring to the transactions, facilities, and storages. For ease of understanding, this research keeps the timings of matrices in minutes, and discusses only the significant preliminary calculations VBA performs to generate these data sets.

Data1 and Data2 are the 1-D matrices that carry general simulation information, the rest all are the 2-D matrices. The Data1 matrix contains H_n (total number of haulers) and L_n (total number of loaders) in the first two columns, which VBA calculates during preliminary calculations. The third and fourth columns contain C_n and W_n , which are the number of crushers and waste dumps respectively. The program calculates the working duration of shifts which it displays in the fifth column from the following formula:-

$$\text{Working duration of shift} = (\text{hours per shift} - \text{non-operating delays per shift} - \text{operating delays per shift}) \times 60$$

The number of shifts to be simulated appears in the sixth column of the Data1 matrix. The working duration of shift multiplied by the number of shifts generates the value of simulation time. It is the time value in minutes for which the model simulates the haulage system. GPSS/H receives the larger dimension of overall mine size in the seventh column of the Data1 matrix. The model uses this dimension to scale down the actual mine distances to computer screen coordinates. R_n is the total number of routes between all loading and all unloading locations, and is calculated by multiplying L_n and D_n . Here D_n is the total number of dump sites that include both the crushers and waste dumps. The ninth column contains the total number of two-lane paths (road sections) present in the mine. The tenth column contains either zero for fixed allocation or one for variable allocation.

The Data2 matrix holds the information on delays and breakdowns, with operator's combined proficiency (%) shown in column 1. From column two to nine, Data2 matrix holds the timings of MTBF and MTTR for the loaders, haulers, crushers and waste dumps. The last column contains the value of delay at a junction for a hauler that does not come across any other hauler at the junction, i.e. for halting before moving on.

The 2-D matrices from H-Info to H-SE hold the information on haulers. The row numbers of H-Info, H-Load, and H-LTime matrices represent the ID numbers of haulers that GPSS/H allocates to its transactions. In this way, H-Info matrix allows each hauler (or transaction) to pick its rated payload, rated top speeds (loaded and empty), hauler type number, and a fixed route number used in fixed allocation. Before filling in the speeds in the H-Info matrix, VBA ensures that the hauler top rated speed is less than the site speed limit. For variable allocation, the simulation model ignores the fixed allocation route number; in other cases it locks the hauler on the mentioned route number. The H-Load and H-LTime matrices hold the values of load and loading time for the haulers at each loader. The preliminary calculations determine these for each hauler-loader match with following formulae (H and L represent a particular hauler and a loader respectively):-

Load received by H from L = load in each bucket of L x total number of passes required to fill H

Loading time of H at L = haulers exchange time at L + time for 1st bucket pass for L + (time for each subsequent bucket pass for L x total number of subsequent passes required to fill H)

To apply the above formulae, VBA calculates the bucket load with help of bucket capacity, bucket fill factor, and ore or waste loose density (as applicable for the loader). The total number of bucket passes is the rounded off value of rated payload of H divided by load in each bucket of L. The simulation program checks that the hauler is not filled beyond its payload and capacity. It allows the overloading of truck by 10% of rated payload.

The row numbers of H-SL and H-SE matrices represent the ID numbers of paths of the road network, and their column numbers represent the hauler type numbers. The hauler type number is different from the ID number of the hauler. To understand this, consider a mine that possesses two types of haulers. Suppose there are four units of type 1 and six units of type 2. In the simulation model, the haulers with ID number one to four will belong to type 1, and those with ID number five to ten will belong to type 2. These two matrices contain the values of speed of loaded and empty haulers respectively, with each value specific to the path characteristics and the hauler type. Before filling in these two matrices, VBA ensures that the user provided speed value is less than the site speed limit and hauler top rated speeds. In another case, if the user defines the speed on a path to be equal to hauler top rated speed (loaded or empty), VBA puts a value of '-1' in the matrix. During the runtime it informs GPSS/H to pick the speed of the hauler from the H-Info matrix.

Table 5.1: Input data sets for the simulation model

Matrix Name		Column Numbers									
		1	2	3	4	5	6	7	8	9	10
Data1	1	Hn	Ln	Cn	Wn	shift duration	no of shifts	max. mine size	Rn	Pn	allocation type
Data2	1	operator proficiency	MTBF (L)	MTTR (L)	MTBF (H)	MTTR (H)	MTBF (C)	MTTR (C)	MTBF (W)	MTTR (W)	delay at junc.
H-Info	1 : Hn	payload (actual)	top speed (loaded)	top speed (un-loaded)	hauler type no	fixed allocation route					
H-Load	1 : Hn	load at L1	load at L2	load at L3	load at L4	load at L5	load at L6	load at L7	load at L8	load at L9	load at L10
H-LTime	1 : Hn	time at L1	time at L2	time at L3	time at L4	time at L5	time at L6	time at L7	time at L8	time at L9	time at L10
H-SL	1 : Pn	SL for H type 1	SL for H type 2	SL for H type 3	SL for H type 4	SL for H type 5	SL for H type 6	SL for H type 7	SL for H type 8	SL for H type 9	SL for H type 10
H-SE	1 : Pn	SE for H type 1	SE for H type 2	SE for H type 3	SE for H type 4	SE for H type 5	SE for H type 6	SE for H type 7	SE for H type 8	SE for H type 9	SE for H type 10
L-Info	1 : Ln	L no	ore or waste	target production	path coordinate (X)	path coordinate (Y)	L coord-inate (X)	L coord-inate (Y)			
D-Info	1 : Dn	D no	no of dump points	target production	path coordinate (X)	path coordinate (Y)	D coord-inate (X)	D coord-inate (Y)	total dump time		
R-Info	1 : Rn	L no	D no	no of paths							
R-Length	1 : Rn	length of path 1	length of path 2	length of path 3	length of path 4	length of path 5	length of path 6	length of path 7	length of path 8	length of path 9	length of path 10
R-Path	1 : Rn	ID of path 1	ID of path 2	ID of path 3	ID of path 4	ID of path 5	ID of path 6	ID of path 7	ID of path 8	ID of path 9	ID of path 10
R-Junc	1 : Rn	ID of junc. before path 1	ID of junc. before path 2	ID of junc. before path 3	ID of junc. before path 4	ID of junc. before path 5	ID of junc. before path 6	ID of junc. before path 7	ID of junc. before path 8	ID of junc. before path 9	ID of junc. before path 10
L: Loader H: Hauler C: Crusher W: Waste dump D: Dump site		Ln : Total number of loaders Hn : Total number of haulers Cn : Total number of crushers Wn: Total number of waste dumps Dn : Cn + Wn					Rn : Total number of routes between all loading and all unloading points (Ln x Dn) Pn : Total number of paths (road sections) SL : Speed of loaded hauler SE : Speed of empty hauler				

The L-Info and D-Info matrices hold the data specific to the loaders and dump sites. The row numbers of the two matrices link to the ID numbers of loaders and dump sites, which GPSS/H allocates to its facilities and storages respectively. The first two columns of the L-Info matrix contain the loader ID number (starting from one) and the material type it is excavating (one for ore, two for waste). The first two columns of D-Info matrix contain the dump site ID number (starting after Ln) and the total number of its dump points. VBA fills the third column of the two matrices with the target production value needed to be met for the particular location by the end of the simulation time (MPR requirement). Preliminary calculations use the following set of formulae to determine the target production:-

$$\text{Target production} = (\% \text{ production contribution for the location} / 100) \times (\text{production per year} / \text{fleet working time per year}) \times \text{simulation time}$$

where, the location refers to a particular loader, crusher or waste dump, and the production refers to ore or waste production, and

$$\text{Fleet working time per year} = [(\text{shifts per day} \times \text{days per year}) - \text{scheduled lost shifts per year} - \text{unscheduled lost shifts per year} - \text{maintenance shifts per year}] \times \text{working duration of shift}$$

GPSS/H uses the data of column four to seven in the L-Info and D-Info matrices for the ATF animation file. These hold the screen coordinates of the ends of the connecting paths and respective locations. The D-Info matrix contains the total dump time in its eighth column, which is the sum of spotting time and actual dumping time.

The R-Info matrix holds the guiding data on all possible routes that are present between the loading and unloading locations. Each row contains the unique route information having a loader ID, dump ID, and the number of involved paths.

The rows of R-Length, R-Path, and R-Junc matrices contain detailed information on the routes selected through the R-Info matrix. The R-Length matrix holds the lengths of all the paths present in the route. The rows of R-Path and R-Junc

matrices contain the ID numbers of paths and junctions that a hauler passes through during its travel on a particular route. Every path uses two different ID numbers that represent their opposite travel directions. The R-Junc matrix contains zero if only one other path connects with current path ID. In case, there are more than two paths joining at a point, VBA allocates it a unique junction ID number (starting after $L_n + D_n$). During the loaded travel on a particular route, the simulation increments the column numbers of R-Length, R-Path, and R-Junc matrices while picking the hauler speeds for each path from H-SL matrix. On the return journey of hauler, the simulation decrements the column numbers of the matrices, and uses the H-SE instead of H-SL matrix.

5.4 Sub-model Structures

GPSS/H constructs the model in blocks which denote the sequence of activities through which the transactions move. It creates one transaction for each hauler at the start of the simulation using a single GENERATE block. The transactions move from one block to the other representing a sequence of events which are separated by increments of time. The simulation clock advances the time to the defined time increment by using ADVANCE block, and the model simulates all the events which have occurred in that time increment. The transactions remain in the system for the duration of the simulation and follow the haulage activities in a cycle.

The simulation model presented in this research applies normal distributions for all the random variables of the haulage cycle, namely loading time, haul and return time, dumping time, and load carried by each hauler. It sets the standard deviation of the normal distributions to 10 percent of the mean values. For the breakdowns of loaders, haulers, and dump sites, the model uses exponential distribution. The model determines the mean of these distributions from the user inputs, where the mean is the value of a variable for which there is a 50 percent probability of occurrence. The reason for selecting such distribution types is the familiarity of these two distributions and their common use in modelling of open pit haulage systems (Çetin, 2004; Tarshizi, 2012). However, the model can easily use any other distribution for the random variables with small changes to the

program. In another case, the software program can also ask the user to select the distribution types (and its related parameters) for the random variables.

The main simulation model implements the load-haul-dump cycle which was discussed in section 3.2. The model handles the concerns of multi-loader multi-dump locations and equipment heterogeneity through manipulation of data in the input matrices. However, to address the additional complexities of breakdowns, haulers bunching, and dispatching, it creates the sub-models. Figure 5.1 shows the general structure of the simulation model having interactions with its sub-models.

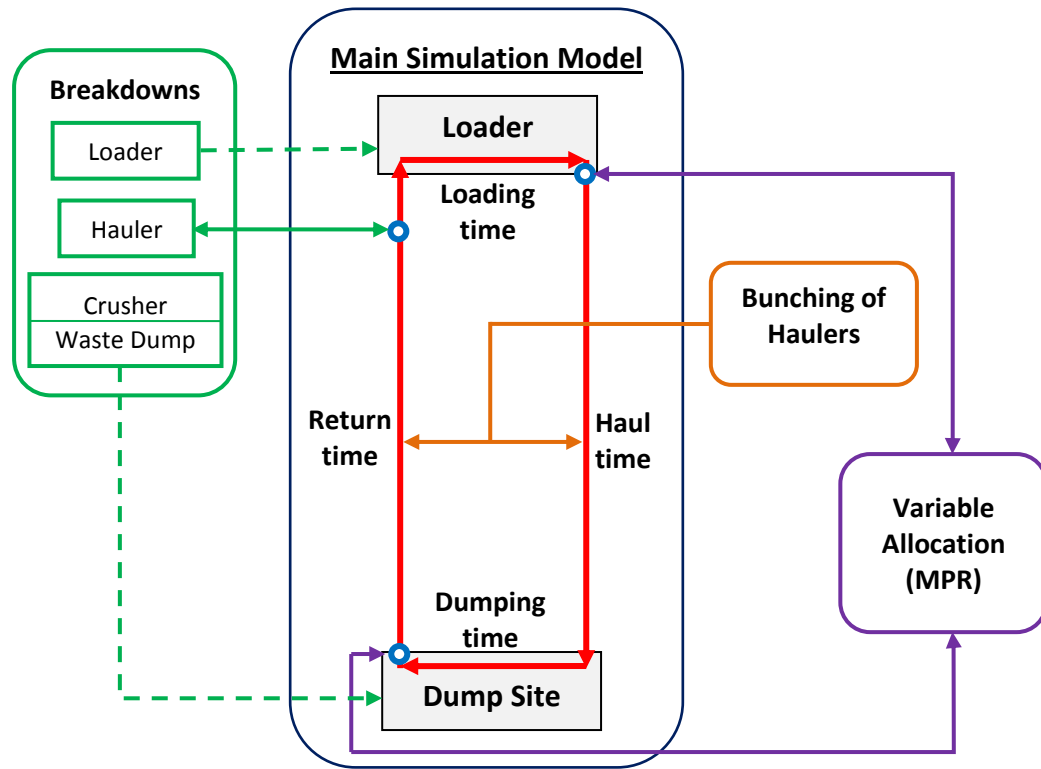


Figure 5.1: General structure of the simulation model

5.4.1 Breakdowns

To introduce the concept of breakdowns in the system, GPSS/H creates four separate sub-models; one each for loaders, haulers, crushers, and waste dumps. Each sub-model randomly chooses one of its entities for failure after the elapse of its exponentially distributed MTBF. In case of loaders and dump sites, GPSS/H

closes the facility or storage by use of FUNAVAIL (facility unavailable) or SUNAVAIL (storage unavailable) blocks. The location remains closed for the transactions for a time equal to its normally distributed MTTR, after which it becomes available again. During the unavailable time, if any transaction approaches the location, it waits in the queue. To handle the breakdown of haulers, the sub-model checks the status of every transaction after every 30 metres distance of hauler travel (30 metre concept explained in the bunching sub-model). If the randomly-chosen-failed-hauler number matches the transaction ID, the sub-model holds the transaction at its current position. It advances the time by an amount equal to its normally distributed MTTR, after which the transaction re-continues its activities from the same point where it failed.


5.4.2 Bunching of Haulers

To handle the situation where haulers bunch, the travel times get corrections from a bunching sub-model. The bunching sub-model captures the haulers movements by adopting a microscopic traffic modelling approach - a framework concept introduced by Jaoua, Riopel and Gamache (2012). It brings the haulage simulation more close to reality, where any hauler cannot take a physical space already occupied by another hauler.

A hauler on a route travels through the paths, where each path may offer a different speed and hence a different travel time to the hauler. The bunching sub-model divides each path into a number of interconnected path segments, each having a length of 30 metres. The 30 metres span represents the approximate length of a hauler plus the safe distance it keeps from the hauler in front. The model treats the path segments as facilities, and the hauler (transaction) travelling on the path seizes these path segments one after the other. The hauler keeps the path segment occupied for the time it takes to travel 30 metres, and then it releases it and seizes the next path segment. If there is no slower hauler travelling in-front, then it completes the journey on the path in the actual time as determined from the input data sets. In other case, it starts following the speed of in-front hauler as soon it reaches its tail. This is due to the longer duration of occupation of the path segments by the leading hauler as compared to the following hauler.

The simulation model uses the SEIZE and RELEASE blocks for the facilities of loaders, junctions and path segments, and ENTER and LEAVE blocks for the storages of crushers and waste dumps. To direct the model to the correct facility and storage, it reserves certain brackets of IDs as shown in Table 5.2. The first 100 numbers are dedicated for the IDs of loaders, dump sites, and junctions. As each path offers one uphill and one downhill lane, so each path represent two ID numbers which show their travel direction. The two brackets of path IDs are from 1 – 50 and 101 – 150, where for instance ‘1’ and ‘101’ represent same path but with opposite travel direction. Each path can have maximum of 500 path segments, which sets the path maximum length to 15 km.

Table 5.2: Brackets of ID numbers for each facility/ storage

Name of the facility/storage	Bracket of ID numbers
Loaders Crushers Waste Dumps Junctions	 1 \longleftrightarrow 100
Path Segments for path 1 Path Segments for path 2 Path Segments for path 3 ↓	101 \longleftrightarrow 600 601 \longleftrightarrow 1100 1101 \longleftrightarrow 1600 ↓
Path Segments for path 50	24601 \longleftrightarrow 25100
Path Segments for path 101 Path Segments for path 102 Path Segments for path 103 ↓	30001 \longleftrightarrow 30500 30501 \longleftrightarrow 31000 31001 \longleftrightarrow 31500 ↓
Path Segments for path 150	54501 \longleftrightarrow 55000

5.4.3 Hauler Dispatching

For the fixed allocation, the transactions remain locked to the assigned route between the facility (loader) and the storage (dump site). The model receives the fixed route number for every hauler from column five of the H-Info matrix. If during the simulation the facility or storage becomes unavailable, the transactions start queuing up at the unavailable location.

For the variable allocation, the transaction approaches the MPR module seeking a fresh assignment at the time of exit from the facility and storage. The MPR module decides the fresh destination after analysing the current production state at all available locations. It does not assign the transaction to an unavailable destination.

This research utilizes the conceptual work of Kolonja and Mutmanský (1993) and Çetin (2004) to develop the MPR dispatching criterion. The objective of the MPR criterion is to achieve the target production set by the user. It assigns the hauler to a location which is most behind in the production schedule while accounting for the en-route haulers. The model computes the current values of K_L or K_D for all the available loaders or dump sites (as applicable) from the following formulae: -

$$K_L = (\text{current simulation time} \times \text{target production of the loader } L / \text{total simulation duration}) - \text{current production of loader } L + \text{production of haulers en-route to loader } L$$

$$K_D = (\text{current simulation time} \times \text{target production of the dump site } D / \text{total simulation duration}) - \text{current production of dump site } D + \text{production of haulers en-route to dump site } D$$

where, K_L is the dispatching parameter used to determine the most lagging loader,

and, K_D is the dispatching parameter used to determine the most lagging dump site (the model checks all the crushers if a hauler carries ore; in other case it checks all the waste dumps).

After unloading, the MPR module checks the current value of K_L for all the available loaders, and allocates the hauler to a loader with the maximum value of K_L . Similarly after loading the ore or waste, it allocates the hauler to an available crusher or waste dump (as applicable) which has the maximum value of K_D . In case the values of K_L or K_D are equal for two locations, the MPR module assigns the hauler to the location with lower ID number (a rare case). The MPR module maintains a separate data log matrix that keeps a record of the current and en-route production for each location. The recorded en-route production is an

expected value for an empty hauler and it is the actual production for a loaded hauler.

5.5 Output Data Sets of the Simulation Model

As shown in Table 5.3, the simulation model manages four output data sets during the simulation run. The purpose of maintaining these data sets is:-

- To create an output file at the end of simulation that contains the results of the complete simulation. VBA uses this file to display the final results after performing the post-simulation calculations.
- To build an ATF file during the simulation runtime. P5 uses the ATF file to animate the system.
- To perform runtime calculations for the simulation model. GPSS/H uses the constantly updated data sets for the functioning of model.

Table 5.3: Output data sets managed by simulation model

Name			Column Numbers									
			1	2	3	4	5	6	7	8	9	10
Loc-Output	Row Numbers	1 : Ln+Dn	% Util.	Entries by haulers	Average time per hauler	Average Queue content	Production (delivered/ received)	MPR number (Kl or Kd)	Load of en-route haulers			
H1-Output		1 : Hn	% Util.	No of cycles	DL	DE	Total wait time	Wait time increment	Wait flag			
H2-Output		1 : Hn	load at L1	load at L2	load at L3	load at L4	load at L5	load at L6	load at L7	load at L8	load at L9	load at L10
H3-Output		1 : Hn	load at D1	load at D2	load at D3	load at D4	load at D5	load at D6	load at D7	load at D8	load at D9	load at D10
L: Loader D: Dump site Hn : Total number of haulers					Ln : Total number of loaders Dn : Total number of dump sites DL : Distance travelled by Loaded hauler (in km) DE : Distance travelled by Empty hauler (in km)							

The Loc-Output data set keeps an updated record for each location (loaders and dump sites). At every instant of simulation time, it holds the current values of percentage utilization, entries by haulers, average time per hauler, average queue

content, and the achieved production. This data set also holds the current value of K_L or K_D and the total load carried by approaching haulers. The model uses the values of column six and seven during the simulation run for MPR variable allocation. The next three data sets record the updated information on the haulers. The H1-Output data set contains the percentage utilization, number of completed cycles, and the distance travelled (loaded and empty) by each hauler. To calculate the hauler utilization, the model uses the values of total wait time, wait time increment, and wait flag during the simulation run. The H2-Output and H3-Output data sets update their records on each delivery and receipt of load by the loader and the dump site respectively.

After receipt of simulation output file by VBA, the program performs post-simulation calculations to generate the final results. The calculations also make use of various inputs that are not transmitted to the simulation model. The program determines following additional outputs with help of simulation output file and user provided inputs: -

TPOH = achieved production during the simulated duration/ total operating hours
during the simulated duration

CPOH = cost of all loaders per operating hour + cost of all haulers per operating
hour

CPT = CPOH / TPOH

Normal TKPH of hauler = average load x average speed

where,

Average load = $[(EW_{FT} \times D_E) + (LW_{FT} \times D_L)] / (D_E + D_L)$

Average speed = $(D_E + D_L) / (\text{total simulation time} + \text{total non-operating delays})$

In above formulae, D_E and D_L are the distances travelled by empty and loaded haulers respectively. EW_{FT} and LW_{FT} are the empty hauler weight on the front

tyres and loaded hauler weight on the front tyres respectively, and determined by following formulae:-

$$EW_{FT} = \text{empty hauler weight} \times (\% \text{ of empty hauler weight on front axle} / 100) / 2$$

$$LW_{FT} = [(\text{total production during simulated duration} / \text{total number of cycles}) + \text{empty hauler weight}] \times (\% \text{ of loaded hauler weight on front axle} / 100) / 2$$

The simulation program determines TKPH for the front tyres of haulers, as front tyres always have a higher loading as compared to rear tyres. If TKPH requirements of the hauler tyres exceed the tyre specifications, the user has following options to improve the situation: -

- Use larger diameter tyre, thus increasing the TKPH limit of the tyres.
- Lower the hauler speed.
- Lower the hauler payload. However, lowering payload produces less effect as compared to lowering speed, as it does not decrease the empty hauler weight.

5.6 Conclusion

The simulation model functions to replicate the truck haulage system operating in an open pit mine. Having due regards to the programming assumptions and the pre-defined boundary conditions, it can take wide variety of input data sets. GPSS/H provides effective simulation of the truck haulage system, as it can represent various activities of the entities in a fair manner. It can also handle the system complexities of breakdowns, haulers' bunching, and dispatching policies by creating the respective sub-models. The efficient management and manipulation of driven data serves as the basis to run the simulation and obtain the desired results.

CHAPTER 6

ANALYSIS OF RESULTS

6.1 Chapter Overview

Every software program works using a different computation methodology and set of assumptions. The correct interpretation and comparison of results depend on the nature of input parameter fed into the programs and their working methodologies.

This chapter analyses the results produced by the simulation program. Firstly, the research verified the functionality of the program where the bugs (errors) were removed. Here, animation helped in verifying the simulation model by keeping a close track of each transaction. Afterwards, the research developed three case studies on hypothetical mines which are discussed in the succeeding paragraphs. The first case study validated the correctness of basic model functionality, and the others two cases examined the simulation results. The CD attached at Appendix D contains the video demonstration of these case studies.

6.2 Case Study 1

In this case study, the research compared the results of a developed simulation program with that was produced using Fleet Production and Cost program (FPC). Krause (2006, p 30) used the parameters of a simple haulage system to explain the FPC production calculation example. This case study used the same example with little modification in order to make it comparable with the simulation program. The example considered a fleet of five units of Caterpillar 793C off-highway trucks and single Caterpillar 944D wheel loader on a simple route. Table 6.1 presents the summary of the example parameters used.

The only change made in the example parameters was the number of passes to fill each hauler, which this research changed from 4.13 to 5 system passes. Krause (2006) used 4.13 passes in the example, which FPC interpreted as 4 subsequent passes other than the first bucket pass. In the first bucket, FPC allocated 13

percent load and in the subsequent four passes, it allocated a full bucket load. Other parameters given in Table 6.1 still matched the example given by Krause (2006), as the material loose density was re-adjusted to match the hauler payload of 222.9 ton.

Table 6.1: Parameters of FPC example (Krause, 2006, p 30) – case study 1

FPC Inputs	
- Fleet	
- Loader (Caterpillar 944D)	1
- Hauler (Caterpillar 793C)	5
- Fleet availability	89.98% (loader: 90%, hauler: 90%)
- Operator efficiency (%)	81%
- At loader – loading time	
- System passes (a)	5
- 1 st bucket pass (b)	0.1 min
- Subsequent bucket pass (c)	0.65 min
- Hauler exchange (d)	0.7 min
- Total loading time (b)+(d)+(a-1)x(c)	3.4 min
- Away from loader - HDR time	
- Haul	2.15 min
- Dump & manoeuvre	1.2 min
- Return	1.17 min
FPC calculated cycle times and hauler load	
- Potential cycle time	7.92 min
- Total cycle time	17.0 min
- Waiting time	9.08 min
- Cycles per hour (de-rated) (after incorporating fleet availability and operator efficiency)	2.6
- Load transported in each cycle	222.9 tons (100% of max GVW)
FPC outputs compared with the simulation program	
- TPOH	2867 ton/hr
- Tons per year (with 7250 scheduled working hours/year)	20 785 750 ton/year
- Normal TKPH (front tyre)	265.12 ton-km/hr
- Fleet CPT	0.249 \$/ton

To represent the parameters of Table 6.1, the research fed the inputs into the FPC and simulation program. Detail of the inputs for both software programs is attached in Appendix A. Both software programs worked on a simple (one road) course, where the haul speed, return speed, and road length were adjusted to produce the equivalent HDR (Haul Dump and Return) time. To correspond to

89.98 percent availability of the fleet, the simulation program assumed MTBF and MTTR of both loader and hauler to be 9 hours and 1 hour respectively. For the comparison of CPT, CPOH for loader and hauler was set to 200 \$/hr and 100 \$/hr respectively. Table 6.2 shows the outputs of the simulation program for 100 consecutive shifts (with each shift having 10 working hours). As the simulation works on random variations constrained by underlying distribution, it may produce different results for each different number of shifts.

Table 6.2: Outputs of simulation program – case study 1

Simulation program outputs			
% Utilization of loader			90.4 %
Average queue contents at loader			2.79
Average loading time			4.19 min
Average % utilization of each hauler			42.66 %
Average number of cycles completed by each hauler (in 1000 working hours)			2585.9
Average production by each hauler (in 1000 working hours)			560078.4 tons
Simulation program outputs compared with FPC			
	Simulation Program	FPC	% difference
TPOH	2800.4 ton/hr	2867 ton/hr	2.3 %
Tons per year (with 7250 working hours/year)	20 302 900 ton/yr	20 785 750 ton/yr	2.3 %
Normal TKPH - average for 5 haulers (with availability of 9 hrs out of 10 hrs)	237.28 ton-km/hr	265.12 ton-km/hr	10.5 %
Normal TKPH - average for 5 haulers (with 100% availability)	262.30 ton-km/hr	265.12 ton-km/hr	1.06 %
Fleet CPT	0.25 \$/ton	0.249 \$/ton	0.4 %

Table 6.2 shows 90.4 percent utilization of the loader. As 2.79 haulers (on average) are kept waiting in the queue during the entire simulation time, the loader worked continuously in theoretical terms. This depicted that one hour of unavailability out of every ten hours reduced the percentage utilization of the loader to 90.4 percent. The loader achieved an average loading time of 4.19 min (actual loading time of 3.4 min affected by operator's efficiency of 81 percent). The 42.66 percent utilization of haulers was attributable to their long waiting times in queue and approximately 10 percent to their unavailability. The simulation model recorded the number of cycles and the delivered production by keeping track of each hauler.

The analysis revealed that the percentage difference in the outputs of the two software programs was attributable to the calculation methodology of hauler load and fleet availability. FPC allocated a fixed load of 222.9 tons/cycle to each hauler, whereas the simulation program applied a normal distribution to the load received by each hauler. With the restriction of overloading up to 10 percent of hauler payload, the average load became less as compared to the fixed hauler load calculated by FPC. In the case of the simulation program, the average load per cycle was 216.59 ton/cycle (average production divided by the average number of cycles), which resulted in the simulation program generating a comparatively conservative production.

For calculating fleet production, FPC de-rated the cycles/hour by incorporating the percentages of fleet availability and operator efficiency. The de-rated values of cycles/hour produced by both software packages were approximately equal (2.6 for FPC and 2.585 for the simulation). However to calculate TKPH, FPC did not incorporate a fleet availability of 90 percent. It generated a higher value of cycles/hour resulting in a higher value of normal average speed of haulers. Contrarily, the simulation represented the fleet unavailability through its repair times (i.e. 1 hour of repair after every 9 hour). In simulation, it remained applicable for both production and TKPH calculations, which resulted in lower TKPH than the corresponding value of FPC. For confirmation, when the simulation program considered 100 percent availability of fleet for 100 shifts, the resultant TKPH was 262.3 ton-km/hr (showing a 1.06 percent difference). For correct interpretation of results, the user must clearly understand these methodological variations of the software programs.

6.3 Case Study 2

In this case study, the research analysed a scenario of a homogeneous fleet composed of four loaders and ten haulers operating at multi-loader multi dump sites. Appendix B contains the detail of input parameters fed into the simulation program. Figure 6.1 shows the graphical layout of the hypothetical open pit mine. As shown, L1.1 and L1.2 were the loaders dedicated to produce ore in the ratio of 60 and 40 percent of the total ore production. The other two loaders L1.3 and L1.4

had the waste extraction targets of 70 and 30 percent of the total waste production. C1 and C2 were the ore crushers, each requiring ore at a ratio of 50 percent of the total produced ore. Both crushers had two dump points each at their locations. W1 and W2 were the waste dumps requiring equal tonnage of dumped waste at all times. Each waste dump location could accommodate two haulers at a time.

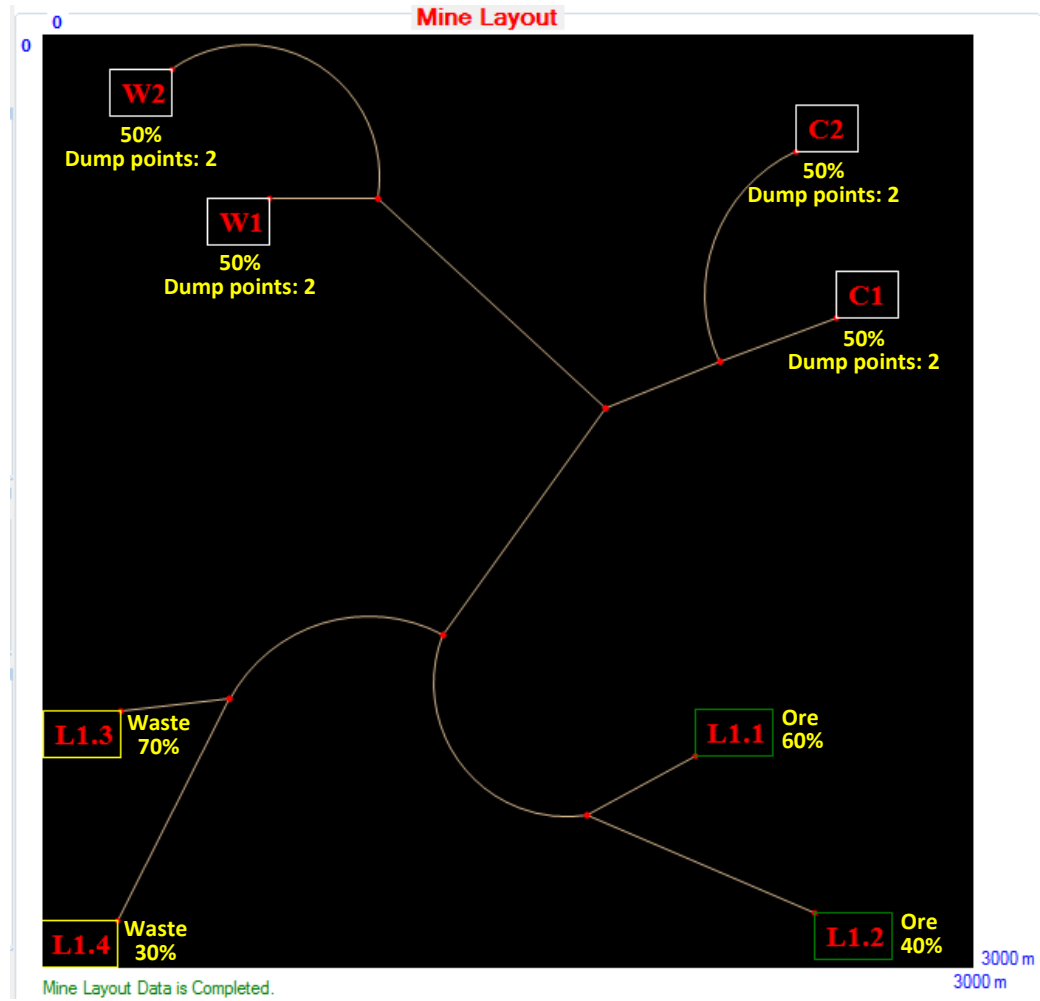


Figure 6.1: Mine layout – case study 2

The fixed allocation system assigned two haulers each for routes L1.1-C1 and L1.2-C2, and three haulers each for routes L1.3-W1 and L1.4-W2. The variable allocation system, on the other hand, assigned fresh locations to the haulers as per the running state of system. It followed MPR policy as discussed in section 5.4.3. Table 6.3 and Table 6.4 present the simulation results for fixed and variable allocation respectively. The results displayed in the tables are with reference to ore and waste, each location, and each hauler for 100 consecutive shifts.

Table 6.3: Results for fixed allocation – case study 2

Simulation Duration

Shifts: 100 Working hrs: 1000 Operating hrs: 1100 Scheduled hrs: 1200

Summary with Reference to Ore and Waste

	No of loaders used	No of haulers used	No of crushers/ waste dumps used	Desired production (ton/year)	Target production (ton/sml duration)	Achieved production (ton/sml duration)	TPOH
Ore	2	4	2	15698596	2308617	2181610 (94.5%)	1983.3
Waste	2	6	2	20785750	3056728	3183735 (104.2%)	2894.3

Total TPOH: 4877.6 Total CPOH: 1800 Total CPT: 0.369

Summary with Reference to Each Location

Location	Utilization (%)	Avg time/ hauler (mins)	Avg queue contents	Haulers Allocated	Total entries by haulers	Target production (ton/sml duration)	Achieved production (ton/sml duration)	TPOH
L 1.1	44.6	5.01	0.05	2	5343	1385170 (60%)	1161754 (83.9%)	1056.1
L 1.2	39.1	5	0.03	2	4688	923447 (40%)	1020288 (110.5%)	927.5
L 1.3	55.6	4.19	0.07	3	7968	2139710 (70%)	1725182 (80.6%)	1568.3
L 1.4	47.2	4.2	0.05	3	6734	917018 (30%)	1458928 (159.1%)	1326.3
C 1	9.4	2.1	0.04	2	5342	1154308 (50%)	1161542 (100.6%)	1055.9
C 2	8.2	2.1	0.04	2	4687	1154308 (50%)	1020068 (88.4%)	927.3
W 1	9.8	1.48	0.02	3	7968	1528364 (50%)	1725182 (112.9%)	1568.3
W 2	8.3	1.49	0.01	3	6732	1528364 (50%)	1458553 (95.4%)	1326

Summary with Reference to Each Hauler

	H 1.1	H 1.2	H 1.3	H 1.4	H 1.5	H 1.6	H 1.7	H 1.8	H 1.9	H 1.10
Utilization %	95	94.6	94.6	95.6	96.4	96.5	96.5	97.1	97.3	96.8
Cycles completed	2676.5	2665	2329.5	2357	2658	2658	2652	2243	2249	2239.5
Dist.-loaded (km)	8031	7996.72	8854	8956.6	9037.2	9037.2	9016.8	10093.83	10123.51	10080
Dist.-empty (km)	8028	7995	8850.2	8956.6	9037.2	9037.2	9016.8	10093.5	10120.5	10077.68
Normal TKPH	744.8	742.8	821.9	831.8	838.1	836.8	835.9	935.9	937.9	934.7
Total Prod.	580767	580775	506817	513252	576625	573993	574564	486205	486563	485786
L 1.1	580767	580987	0	0	0	0	0	0	0	0
L 1.2	0	0	506817	513472	0	0	0	0	0	0
L 1.3	0	0	0	0	576625	573993	574564	0	0	0
L 1.4	0	0	0	0	0	0	0	486368	486775	485786
C 1	580767	580775	0	0	0	0	0	0	0	0
C 2	0	0	506817	513252	0	0	0	0	0	0
W 1	0	0	0	0	576625	573993	574564	0	0	0
W 2	0	0	0	0	0	0	0	486205	486563	485786

Table 6.4: Results for variable allocation – case study 2

Simulation Duration

Shifts: 100 Working hrs: 1000 Operating hrs: 1100 Scheduled hrs: 1200

Summary with Reference to Ore and Waste

	No of loaders used	No of haulers used	No of crushers/ waste dumps used	Desired production (ton/year)	Target production (ton/sml duration)	Achieved production (ton/sml duration)	TPOH				
Ore	2	Variable	2	15698596	2308617	2299412 (99.6%)	2090.4				
Waste	2	Variable	2	20785750	3056728	3048051 (99.7%)	2771				
Total TPOH:		4861.4		Total CPOH:		1800		Total CPT:		0.37	

Summary with Reference to Each Location

Location	Utilization (%)	Avg time/ hauler (mins)	Avg queue contents	Haulers Allocated	Total entries by haulers	Target production (ton/sml duration)	Achieved production (ton/sml duration)	TPOH
L1.1	52.8	5	0.07	Variable	6347	1385170 (60%)	1380412 (99.7%)	1254.9
L1.2	35.2	5	0.02	Variable	4229	923447 (40%)	919644 (99.6%)	836
L1.3	69.1	4.19	0.21	Variable	9880	2139710 (70%)	2135752 (99.8%)	1941.6
L1.4	29.5	4.2	0.02	Variable	4221	917018 (30%)	913156 (99.6%)	830.1
C1	9.2	2.1	0.02	Variable	5282	1154308 (50%)	1150108 (99.6%)	1045.6
C2	9.3	2.1	0.02	Variable	5291	1154308 (50%)	1149304 (99.6%)	1044.8
W1	8.7	1.49	0	Variable	7046	1528364 (50%)	1524021 (99.7%)	1385.5
W2	8.7	1.48	0	Variable	7051	1528364 (50%)	1524031 (99.7%)	1385.5

Summary with Reference to Each Hauler

	H 1.1	H 1.2	H 1.3	H 1.4	H 1.5	H 1.6	H 1.7	H 1.8	H 1.9	H 1.10
Utilization %	94.7	95.5	95.6	94.6	95.4	95.9	95.1	95.2	94.3	95.6
Cycles completed	2456.5	2475	2474	2457	2467	2491.5	2458.5	2463	2446	2480.5
Dist.-loaded (km)	8933.75	9054	9013.5	8957.53	8981.4	9054.6	8978.9	8957.05	8929.4	9085.65
Dist.-empty (km)	8932.51	9054.15	9011.8	8954.4	8981.4	9051.96	8975.4	8957.05	8929.85	9082.25
Normal TKPH	828.6	839.8	836.1	829.9	832.2	839.2	833.1	829.4	828.2	842.5
Total Prod.	533142	537101	537132	531646	533790	539686	534225	531976	530721	538045
L1.1	139941	134114	146163	138781	140143	138983	134256	141641	130391	136000
L1.2	86830	90850	92493	95046	98858	96384	97529	88599	91020	82034
L1.3	224222	219077	200925	210124	205011	211994	207886	214807	218319	223389
L1.4	82149	93285	97794	87877	90022	92325	94554	87148	91179	96822
C1	112092	112482	113221	113684	119874	118282	120645	117880	114116	107830
C2	114679	112257	125434	120142	119126	117086	111140	112141	107295	110004
W1	154088	151321	152630	148016	147034	160883	148684	151941	153653	155771
W2	152283	161041	145846	149804	147755	143436	153756	150014	155656	164439

Figure 6.2 presents the productions achieved for ore, waste, and each location in terms of their differences from the set targets. For fixed allocation, the productions achieved by each category remained inconsistent with reference to the set targets. This was due to the reason that fixed allocation productions depended mainly on the number of allocated haulers and the involved distances. Contrarily, the variable allocation attempted constantly to catch up the set targets. It resulted

in achieving more similar production differences from the targets set for each category. The overall production of the system (ore plus waste) for variable allocation (5.347463 Million tons) was however a little less than the overall production achieved by fixed allocation (5.365345 Million tons).

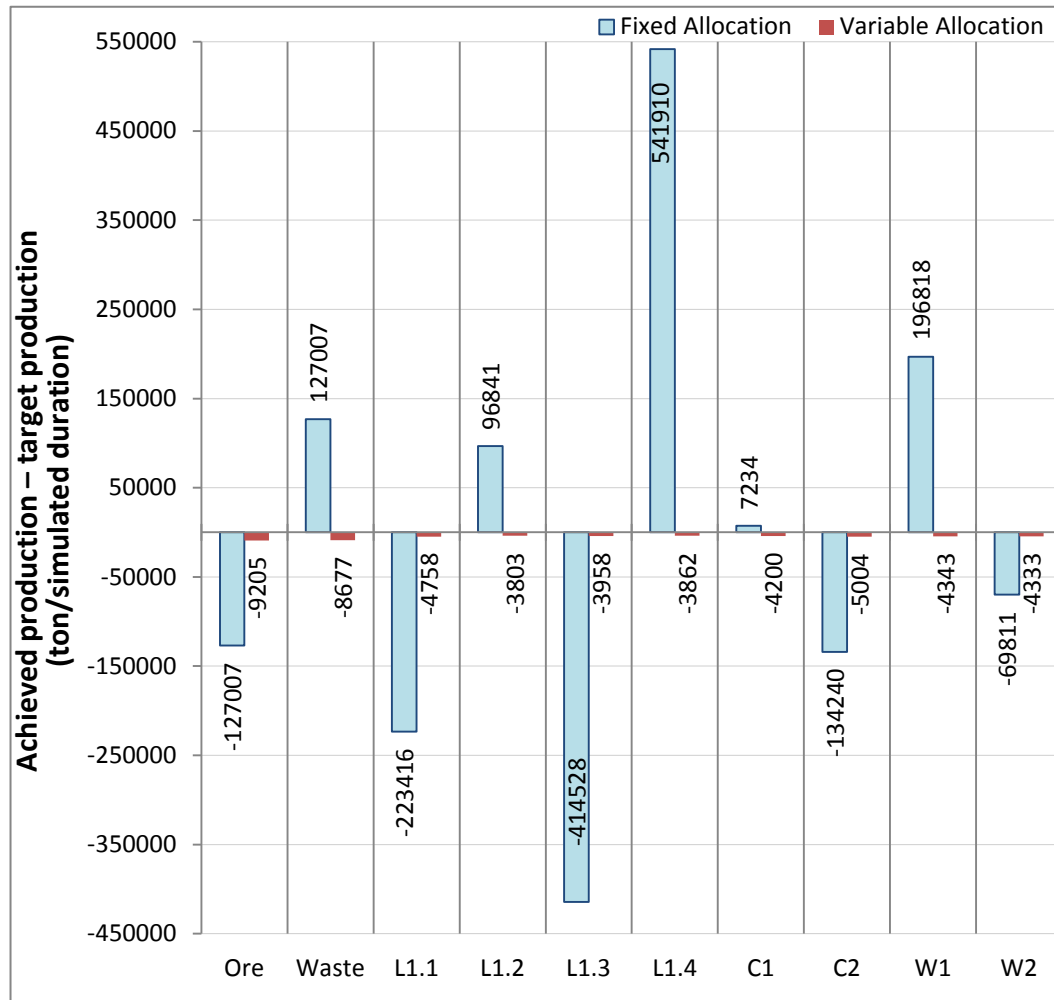


Figure 6.2: Difference between achieved production and target production for ore, waste, and each location – case study 2

Figure 6.3 presents the tonnage transported by each hauler during 100 shifts. For the fixed allocation situation, each set of haulers on the assigned routes transported different tonnages. The cycle time of each route caused major influences on the haulers' production. Contrarily, the haulers did not stick to one route during variable allocation. By travelling on various routes, the haulers completed their cycles in different durations thus generating an averaged production for each hauler.

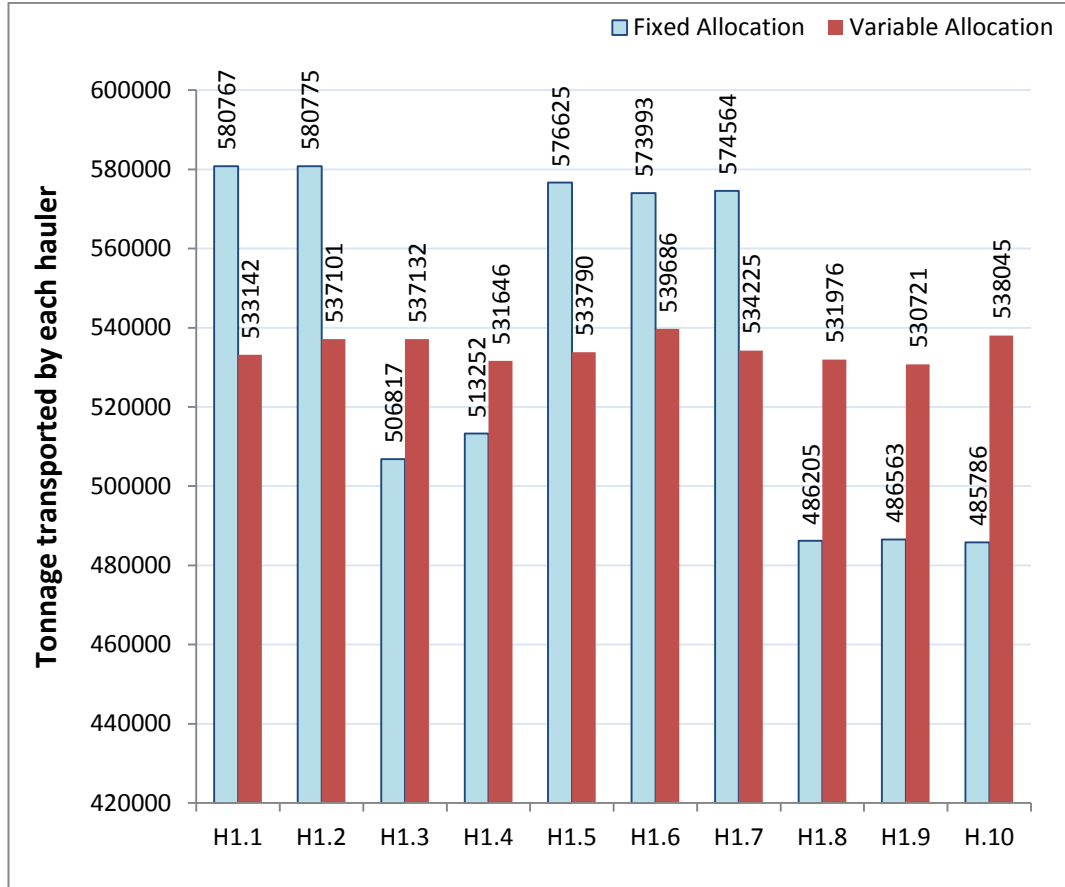


Figure 6.3: Tonnage transported by each hauler – case study 2

6.4 Case Study 3

This case study analysed the performance of a heterogeneous fleet under two scenarios. Both scenarios incorporated stepwise modifications in the parameters of case study 2. Scenario A employed different type of loaders for ore production, and scenario B considered two types of haulers operating in the open pit mine.

6.4.1 Scenario A

Scenario A considered different types of loaders for extraction of ore and waste. All other parameters remained the same as for case study 2. The loaders extracting waste L2.1 and L2.2 had the same specifications i.e. for Caterpillar front end loader 994D as of case study 2; however, this scenario considered two units of Caterpillar power shovel 4100 (L1.1 and L1.2) for ore production. Table 6.5 shows the detail of loader parameters fed into the simulation program.

Table 6.5: Parameters of the loaders – case study 3 (scenario A)

Total number of loader types	2	
	Type 1 (L1.1, L1.2)	Type 2 (L2.1, L2.2)
- Manufacture	Caterpillar	Caterpillar
- Class	Power Shovel	Front End Loader
- Model	4100	994D
- Number of units in mine	2	2
- Rated load in bucket (tons)	76.204 tons	34.473 tons
- Capacity (m ³)	42.82 m ³	18.73 m ³
- Bucket fill factor (%)	100 %	100 %
- Time - 1 st bucket pass	0.05 min	0.1 min
- Time - each subsequent pass	0.5 min	0.65 min
- Hauler exchange time	0.7 min	0.7 min
- Cost per operating hour	300 \$/hr	200 \$/hr

Figure 6.4 and Figure 6.5 depicts the results for scenario A. Figure 6.4 shows the productions achieved for ore, waste, and each location in terms of their differences from the set targets, and Figure 6.5 shows the tonnage transported by each hauler. Since the loaders employed for ore production had larger bucket capacities with faster cycle times than the loaders employed in case study 2, the overall ore production for fixed allocation increased in this scenario. However, it still generated variations in the achieved production figures with reference to the targets set for each location. Contrarily, the variable allocation evenly distributed the increased production capability of the system, and maintained constant differences from the respective targets. The variable allocation caused the tonnages transported by all haulers to be more similar as compared to the corresponding tonnages transported in the fixed allocation system. The total production of the system for variable allocation (5.759545 Million tons) was however a little less than the total production achieved by fixed allocation (5.800539 Million tons).

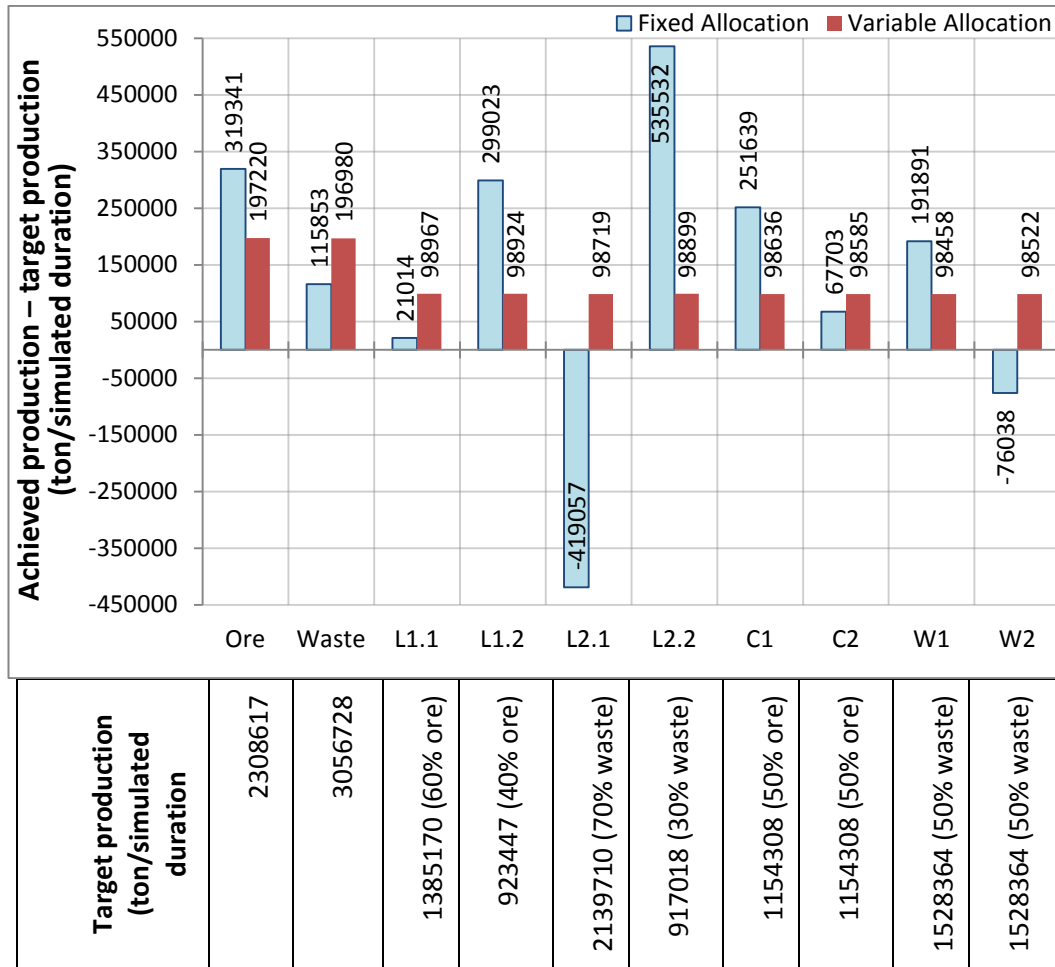


Figure 6.4: Difference between achieved production and target production for ore, waste, and each location – case study 3 (scenario A)

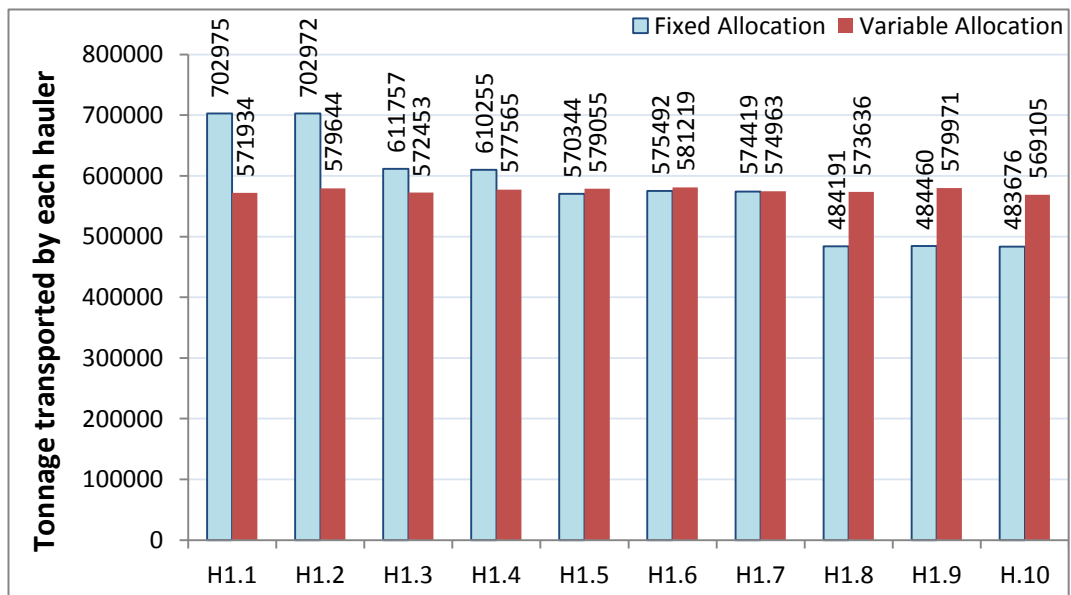


Figure 6.5: Tonnage transported by each hauler – case study 3 (scenario A)

6.4.2 Scenario B

Scenario B incorporated heterogeneity of haulers in the system. All other input parameters are the same as for scenario A. This scenario considered that two out of ten 793C haulers got old, and the maintenance team reduced the maximum speed limits of these two haulers. For fixed allocation, the mine management assigned the old haulers to loaders L1.2 and L2.2 (the loaders which were achieving more production than the set targets in scenario A). Table 6.6 shows the parameters for the haulers and their allocation for fixed allocation.

Table 6.6: Parameters of haulers – case study 3 (scenario B)

- Total number of hauler types	2	
	Type 1	Type 2
- Manufacture	Caterpillar	Caterpillar
- Model	793C	793C-OLD
- Number of units in mine	8	2
- Routes (for fixed allocation)	H1.1: L1.1-C1 H1.2: L1.1-C1 H1.3: L1.2-C2 H1.4: L2.1-W1 H1.5: L2.1-W1 H1.6: L2.1-W1 H1.7: L2.2-W2 H1.8: L2.2-W2	H2.1: L1.2-C2 H2.2: L2.2-W2
- Payload index (tons)	222.9 tons	222.9 tons
- Capacity (m ³)	129.2 m ³	129.2 m ³
- Top speed (loaded)	54 km/hr	20 km/hr
- Top speed (empty)	60 km/hr	30 km/hr
- Cost per operating hour	100 \$/hr	80 \$/hr

Figure 6.6 and Figure 6.7 depicts the results of scenario B. For fixed allocation, the comparison with scenario A showed a reduction of achieved production by L1.2, L2.2, C2, and W2 due to employment of slower haulers on their routes. The tonnages transported by H2.1 and H2.2 were less than those transported by other haulers travelling on the same routes (H1.3 and H1.7, H1.8 respectively) due to the longer cycle times of the slower haulers. The comparison with corresponding haulers of scenario A also showed a reduction in transported tonnages by H1.3, H1.7, and H1.8 due to increased bunching of haulers.

For the variable allocation case, haulers of type 2 transported less average tonnage as compared to haulers of type 1. The MPR criteria, however, evenly distributed the reduced production capability of the system to all the locations. In this scenario, the total system production for variable allocation (5.340604 Million tons) was a little more than the total production achieved by fixed allocation (5.254263 Million tons). The animation showed that the system generated less production in the fixed allocation system due to increased haulers' bunching (faster hauler following a slower hauler on fixed routes).

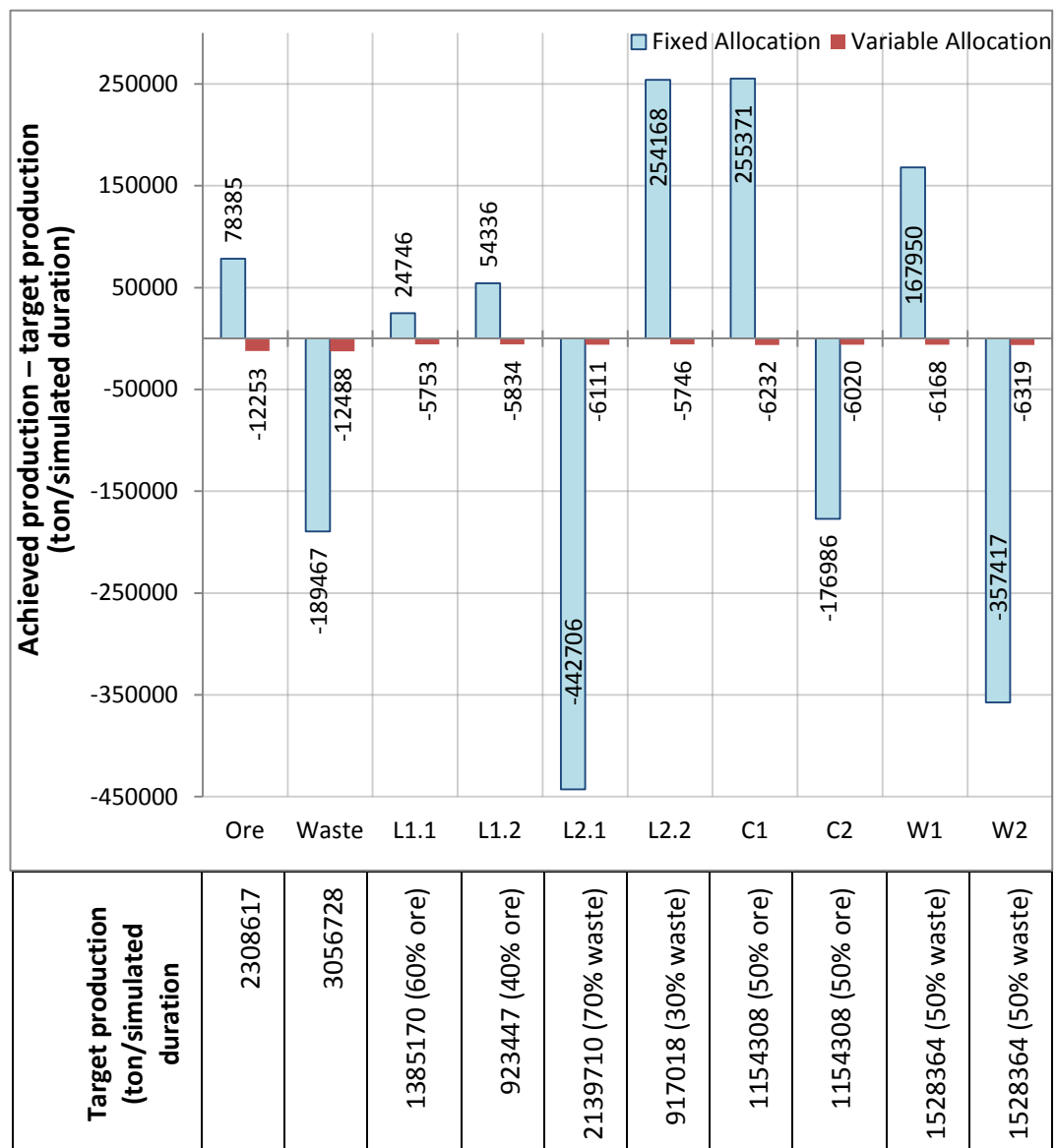


Figure 6.6: Difference between achieved production and target production for ore, waste, and each location – case study 3 (scenario B)

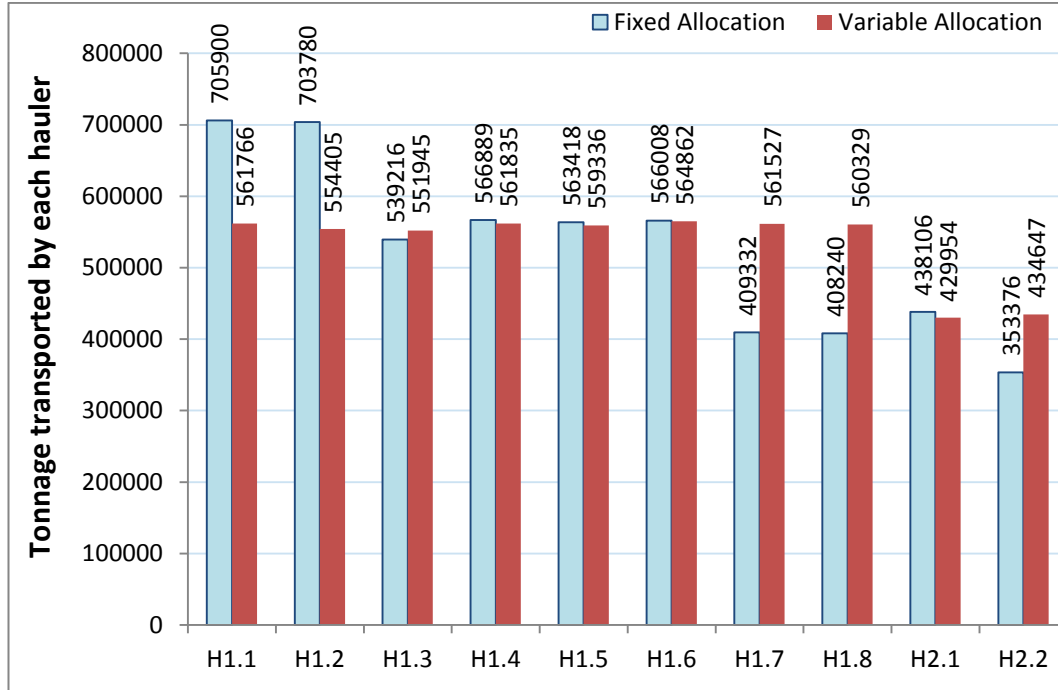


Figure 6.7: Tonnage transported by each hauler – case study 3 (scenario B)

6.5 Conclusion

The research draws the following conclusions from the analysis of results: -

- The user must understand the working methodology and set of assumptions used in the software programs to correctly interpret the results.
- Selection of dispatching policy is a mine specific problem.
- If it is a priority to achieve the production targets of loaders and/or dump locations, the MPR variable allocation is a better option than the fixed allocation.
- The MPR variable allocation evenly distributes the production capability of the whole system in the ratio of the target production levels set for each location.
- The MPR variable allocation may reduce the overall production capability of the system (ore plus waste). It is more prominent in cases when it dispatches several haulers to the same location that is lagging in production due to an earlier breakdown. This causes queuing at the location (this aspect is more apparent in the animation section).

CHAPTER 7

SUMMARY AND CONCLUSION

7.1 Summary

Open pit mines commonly employ truck haulage systems due to various inherent advantages. Mine management can utilize various strategies and methods to reduce the overall cost of the haulage system. Amongst various techniques, simulation proves to be a powerful tool in estimating realistic system behaviour.

An exact prediction about the future of a mining project is difficult due to the diversity and dynamic nature of all the involved factors. Simulation techniques, however, are capable of producing unbiased information about the likelihood and possible future of a mining project. On the other hand, simulation results depend considerably on the accuracy of input parameters and its modelling characteristics.

Some significant factors that add complexity to the truck haulage system include uncertainty, fleet heterogeneity, multi-locations, haulers' bunching, and dispatching policy. The developed simulation program demonstrates the power of computerized simulation in addressing these complexities by integrating GPSS/H, P5, and VBA. The user provides numerical and graphical inputs through the interface provided by VBA, then GPSS/H runs the simulation model and P5 animates the system. The outputs of the simulation program mainly focus on total CPT, achieved production by the fleet components and dump locations, fleet utilizations, and TKPH of the haulers.

Simulation model is stochastic and it functions on the guidance of input data sets. It uses a normal distribution for all the random variables of haulage cycle, and an exponential distribution for the unavailability of fleet and dump locations. The model handles the complexities of multi-locations and fleet heterogeneity through manipulation of the input data sets, and creates sub-models to address the concerns of breakdowns, haulers' bunching and dispatching protocols.

The animation section helps in analysing the results produced by the simulation program. This research considered three case studies to study the results and make

comparisons between fixed and variable (MPR) allocation. The MPR policy proves to be more suitable for mines having strict quality control objectives.

7.2 Conclusion

Open pit mines exhibit dynamic and uncertain environments, where load-haul-dump cycles are likely to vary with time. Discrete event simulation associated with animated visuals can effectively represent the variable and interlinked nature of mining operations.

The developed simulation program utilized the power of animated simulation to analyse the truck haulage systems operating in open pit mines. The user can use the simulation program to: -

- Acquire guidance in decision making process.
- Determine a cost effective haulage strategy.
- Evaluate various equipment requirements for future haulage operations.
- Analyse the effects on the system productivity by varying the fleet sizes, fleet combinations, fleet parameters, operational parameters, haulage conditions and layout geometry, etc.
- Implement and analyse a wide variety of mine layouts with multi-loader, multi-dump sites.
- Analyse the system performance by introducing different types of loaders and haulers (fleet heterogeneity).
- Analyse a more realistic behaviour of the transport system based on an increase or decrease in the bunching of haulers.
- Draw comparisons between different dispatching policies in order to meet the mine requirements (fixed and MPR variable allocation in present case).
- Analyse the effects of equipment breakdowns on system productivity.

7.3 Future Work

The research focused on developing a general-purpose, data-driven, and user-friendly simulation software program, where the user can implement any planned or actual specifications of the mine haulage system. The area of research is fairly

large and contains wide margins for improvements. For future research the following recommendations are made:-

- Validate the simulation results by obtaining the statistical parameters of a real operational mine.
- Link the manufacturer's database of loaders and haulers with the software.
- Incorporate elaborated details on haulage costs in the simulation program that includes fuel, maintenance, and hourly costs etc.
- Provide the user with the ability to select other variable allocation policies along with MPR. These include: minimum hauler waiting time, minimum loader wait time, minimum loader saturation, minimum hauler cycle time, earliest loading loader, and longest waiting loader.
- Eliminate or reduce the constraints of using the simulation program. These include limits on maximum numbers of loaders, haulers, dump sites, road sections, and length of each road section.
- Incorporate the option in simulation program to:-
 - Select any distribution type for the random variables of haulage cycle. The simulation program should offer a minimum of five distribution types including normal, log-normal, exponential, tri-angular (left-skewed and right skewed), and Weibull functions.
 - Allow single or double side loading from the loader.
 - Allow material blending at loaders and crushers.
 - Mark the parking area in the mine layout. The haulers should travel from and to the parking area at the start and end of each shift respectively.
 - Mark the fuel filling station in the mine layout. The simulation model should send/ stop the haulers for refuelling at the correct mileages.
 - Allocate a new location to the hauler, if the previously assigned location becomes unavailable during the hauler's travel time (applicable for variable allocation policies).
 - Link two locations in the mine layout through various routes.

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Appendix A

Case Study 1

Input Parameters for the Simulation Program and FPC

	Simulation Software	FPC
1. <u>Project Basics</u>		
- Ore production per year	-	-
- Waste production per year	20 785 750 tons	20 785 750 tons
- Currency unit	USD	USD
- Waste bank density	2.5 ton/m ³	2.5 ton/m ³
- Waste loose density	2.38 ton/m ³	2.38 ton/m ³
2. <u>Roster and Time Delays</u>		
- Hours per shift	10 hr/shift	10 hr/shift
- Shifts per day	2	-
- Standard delays		
- Non-operating delays/shift	0	0
- Operating delays/shift	0	Not applicable in FPC
- Scheduled lost shifts/year	5 (to generate 7250 working hrs/years)	
- Unscheduled lost shifts/year	0	
- Maintenance shifts/year	0	
- Operational delays		
- MTBF for loaders	9 hrs	Availability: 90%
- MTTR for loaders	1 hr	
- MTBF for haulers	9 hrs	Availability: 90%
- MTTR for haulers	1 hr	
- Delay at road junctions	0.15 min	Bunching: Average
- Operator efficiency (%)	81%	81%
3. <u>Hauler</u>		
- Total number of hauler types	1	1
- Manufacture	Caterpillar	Caterpillar
- Class	Rear Dump Truck	Truck
- Model	793C	793C
- Number of units in mine	5	5
- Payload index (tons)	222.9 tons	222.9 tons
- Capacity (m ³)	129.2 m ³	129.2 m ³
- Top speed (loaded)	54 km/hr	-
- Top speed (empty)	60 km/hr	-
- Cost per operating hour	100 \$/hr	100 \$/hr

4. <u>Loader</u>		
- Total number of loader types	1	1
- Manufacture	Caterpillar	Caterpillar
- Class	Front End Loader	Wheel Loader
- Model	994D	994D
- Number of units in mine	1	1
- Rated load in bucket (tons)	34.473 tons	34.473 tons
- Capacity (m ³)	18.73 m ³	18.73 m ³
- Bucket fill factor (%)	100 %	100 %
- Time - 1 st bucket pass	0.1 min	0.1 min
- Time - each subsequent pass	0.65 min	0.65 min
- Hauler exchange time	0.7 min	0.7 min
- Cost per operating hour	200 \$/hr	200 \$/hr
5. <u>Mine Layout & Parameters</u>		
- Overall size of mine	2000 m x 2000 m	Not applicable
- Number of crushers	0	Single haul course
- Number of waste dumps	1	
- Maximum speed limit on site	55 km/hr	Not applicable
- At waste dumps		
- Hauler spot time	0.2 min	Dump & manoeuvre: 1.2 min
- Hauler dump time	1 min	
- Dump points	5	Passing allowed at dump
- Haul road geometry		
- Title of road section	1	1
- Length	900 m	900 m
- Curve angle	0	0
- Grade-ability %	0	0
- Rolling resistance %	0	0
- Speed - each hauler type (loaded)	26.2 km/hr	26.2 km/hr
- Speed - each hauler type (empty)	55 km/hr	55 km/hr
6. <u>Number of shifts to be simulated</u>		
- Number of shifts	100	Not applicable

Case Study 2**Input Parameters for the Simulation Program**

	Simulation Software
<u>1. Project Basics</u>	
- Ore production per year	15 698 596 tons
- Waste production per year	20 785 750 tons
- Currency unit	USD
- OSR	1.1651
- Ore bank density	2.2 ton/m ³
- Ore loose density	2.0 ton/m ³
- Waste bank density	2.5 ton/m ³
- Waste loose density	2.38 ton/m ³
<u>2. Roster and Time Delays</u>	
- Hours per shift	12 hr/shift
- Shifts per day	2
- Standard delays	
- Non-operating delays/shift	1 hr
- Operating delays/shift	1 hr
- Scheduled lost shifts/year	26
- Unscheduled lost shifts/year	12
- Maintenance shifts/year	12
- Operational delays	
- MTBF for loaders	9 hrs
- MTTR for loaders	1 hr
- MTBF for haulers	9 hrs
- MTTR for haulers	1 hr
- MTBF for crushers	23 hr
- MTTR for crushers	1 hr
- MTBF for waste dumps	99 hr
- MTTR for waste dumps	1 hr
- Delay at road junctions	0.25 min
- Operator efficiency (%)	81%
<u>3. Hauler</u>	
- Total number of hauler types	1
- Manufacture	Caterpillar
- Class	Rear Dump Truck
- Model	793C
- Number of units in mine	10
- Payload index (tons)	222.9 tons
- Capacity (m ³)	129.2 m ³
- Top speed (loaded)	54 km/hr

- Top speed (empty)			60 km/hr		
- Cost per operating hour			100 \$/hr		
4. <u>Loader</u>					
- Total number of loader types			1		
- Manufacture			Caterpillar		
- Class			Front End Loader		
- Model			994D		
- Number of units in mine			4		
- Rated load in bucket (tons)			34.473 tons		
- Capacity (m ³)			18.73 m ³		
- Bucket fill factor (%)			100 %		
- Time - 1 st bucket pass			0.1 min		
- Time - each subsequent pass			0.65 min		
- Hauler exchange time			0.7 min		
- Cost per operating hour			200 \$/hr		
5. <u>Mine Layout & Parameters</u>					
- Overall size of mine			3000 m x 3000 m		
- Number of crushers			2		
- Number of waste dumps			2		
- Maximum speed limit on site			55 km/hr		
- At waste dumps					
- Hauler spot time			0.2 min		
- Hauler dump time			1 min		
- Dump points			2		
- At crushers					
- Hauler spot time			0.2 min		
- Hauler dump time			1.5 min		
- Dump points			2		
- Haul road geometry					
No	Title	Length	Curve angle	Speed loaded	Speed Empty
1	Central	900		26.2	55
2	To O loaders	900	-120	35	60
3	To L1.1	400		25	50
4	To L1.2	800		25	50
5	To W loaders	800	-90	35	60
6	To L1.3	350		25	50
7	To L1.4	800		25	50
8	To crushers	400		30	57
9	To C1	400		30	57
10	To C2	800	90	30	57
11	To dumps	1000		30	57
12	To W1	350		30	57
13	To W2	1000	-135	30	57
6. <u>Number of shifts to be simulated</u>					
- Number of shifts				100	

GPSS/H Code

```
INTEGER  &X,&LDRDOWN,&CRSDOWN,&WASDOWN,&HLRDOWN,_
&LDRFLAG,&CRSFLAG,&WASFLAG,&HLRFLAG
INTEGER  &HFNO
REAL    &DATA1(10),&DATA2(10),&HFTIME,&LFTIME,&CFTIME,&WFTIME
*
MYFILE      FILEDEF      'C:\\PROJECT\\SIMINPUT.GPS'
OUTFILE      FILEDEF      'C:\\PROJECT\\SIMOUTPUT.GPS'
OUTANIM      FILEDEF      'C:\\PROJECT\\ANIM.ATF'
*
GETLIST
FILE=MYFILE,&DATA1(1),&DATA1(2),&DATA1(3),&DATA1(4),&DATA1(5),_
&DATA1(6),&DATA1(7),&DATA1(8),&DATA1(9),&DATA1(10)
GETLIST
FILE=MYFILE,&DATA2(1),&DATA2(2),&DATA2(3),&DATA2(4),&DATA2(5),_
&DATA2(6),&DATA2(7),&DATA2(8),&DATA2(9),&DATA2(10)
HINFO MATRIX      ML,&DATA1(1),5
DO &X=1,&DATA1(1)
GETLIST
FILE=MYFILE,ML(HINFO,&X,1),ML(HINFO,&X,2),ML(HINFO,&X,3),_
ML(HINFO,&X,4),ML(HINFO,&X,5)
ENDDO
HLOAD MATRIX      ML,&DATA1(1),10
DO &X=1,&DATA1(1)
GETLIST
FILE=MYFILE,ML(HLOAD,&X,1),ML(HLOAD,&X,2),ML(HLOAD,&X,3),_
ML(HLOAD,&X,4),ML(HLOAD,&X,5),ML(HLOAD,&X,6),ML(HLOAD,&X,7),_
ML(HLOAD,&X,8),ML(HLOAD,&X,9),ML(HLOAD,&X,10)
ENDDO
HLTIME MATRIX      ML,&DATA1(1),10
DO &X=1,&DATA1(1)
GETLIST
FILE=MYFILE,ML(HLTIME,&X,1),ML(HLTIME,&X,2),ML(HLTIME,&X,3),_
ML(HLTIME,&X,4),ML(HLTIME,&X,5),ML(HLTIME,&X,6),ML(HLTIME,&X,7),_
ML(HLTIME,&X,8),ML(HLTIME,&X,9),ML(HLTIME,&X,10)
ENDDO
```



```

HSL  MATRIX      ML,&DATA1(9),10
      DO &X=1,&DATA1(9)
      GETLIST
      FILE=MYFILE,ML(HSL,&X,1),ML(HSL,&X,2),ML(HSL,&X,3),ML(HSL,&X,4),_
ML(HSL,&X,5),ML(HSL,&X,6),ML(HSL,&X,7),ML(HSL,&X,8),ML(HSL,&X,9),_
ML(HSL,&X,10)
      ENDDO
HSE  MATRIX      ML,&DATA1(9),10
      DO &X=1,&DATA1(9)
      GETLIST
      FILE=MYFILE,ML(HSE,&X,1),ML(HSE,&X,2),ML(HSE,&X,3),ML(HSE,&X,4),_
ML(HSE,&X,5),ML(HSE,&X,6),ML(HSE,&X,7),ML(HSE,&X,8),ML(HSE,&X,9),_
ML(HSE,&X,10)
      ENDDO
LINFO MATRIX      ML,&DATA1(2),7
      DO &X=1,&DATA1(2)
      GETLIST
      FILE=MYFILE,ML(LINFO,&X,1),ML(LINFO,&X,2),ML(LINFO,&X,3),_
ML(LINFO,&X,4),ML(LINFO,&X,5),ML(LINFO,&X,6),ML(LINFO,&X,7)
      ENDDO
DINFO MATRIX      ML,&DATA1(3)+&DATA1(4),8
      DO &X=1,&DATA1(3)+&DATA1(4)
      GETLIST
      FILE=MYFILE,ML(DINFO,&X,1),ML(DINFO,&X,2),ML(DINFO,&X,3),_
ML(DINFO,&X,4),ML(DINFO,&X,5),ML(DINFO,&X,6),ML(DINFO,&X,7),ML(DINFO,&X,8)
      ENDDO
RINFO MATRIX      MH,&DATA1(8),3
      DO &X=1,&DATA1(8)
      GETLIST
      FILE=MYFILE,MH(RINFO,&X,1),MH(RINFO,&X,2),MH(RINFO,&X,3)
      ENDDO
RLENGTH MATRIX    MH,&DATA1(8),10
      DO &X=1,&DATA1(8)
      GETLIST      FILE=MYFILE,MH(RLENGTH,&X,1),MH(RLENGTH,&X,2),_
MH(RLENGTH,&X,3),MH(RLENGTH,&X,4),MH(RLENGTH,&X,5),MH(RLENGTH,&X,6),_
MH(RLENGTH,&X,7),MH(RLENGTH,&X,8),MH(RLENGTH,&X,9),MH(RLENGTH,&X,10)
      ENDDO
RPATH MATRIX      MH,&DATA1(8),10
      DO &X=1,&DATA1(8)

```

```

        GETLIST
        FILE=MYFILE,MH(RPATH,&X,1),MH(RPATH,&X,2),MH(RPATH,&X,3),_
MH(RPATH,&X,4),MH(RPATH,&X,5),MH(RPATH,&X,6),MH(RPATH,&X,7),_
MH(RPATH,&X,8),MH(RPATH,&X,9),MH(RPATH,&X,10)
        ENDDO
RJUNC MATRIX      MB,&DATA1(8),10
        DO &X=1,&DATA1(8)
        GETLIST
        FILE=MYFILE,MB(RJUNC,&X,1),MB(RJUNC,&X,2),MB(RJUNC,&X,3),_
MB(RJUNC,&X,4),MB(RJUNC,&X,5),MB(RJUNC,&X,6),MB(RJUNC,&X,7),_
MB(RJUNC,&X,8),MB(RJUNC,&X,9),MB(RJUNC,&X,10)
        ENDDO
*
H1OUT MATRIX      ML,&DATA1(1),7
H2OUT MATRIX      ML,&DATA1(1),10
H3OUT MATRIX      ML,&DATA1(1),10
LOCOUT MATRIX     ML,&DATA1(2)+&DATA1(3)+&DATA1(4),4
        DO &X=1,&DATA1(2)+&DATA1(3)+&DATA1(4)
        LET    ML(LOCOUT,&X,1)=0
        LET    ML(LOCOUT,&X,2)=0
        LET    ML(LOCOUT,&X,3)=-1000000000      'MLPR check initialized
        LET    ML(LOCOUT,&X,4)=0
        ENDDO
        DO &X=1,&DATA1(1)
        LET    ML(H1OUT,&X,1)=-1.0      'initializing utilization of each hauler
        ENDDO
*
RNDNO FUNCTION    RN1,C2      'generates a random no from 0 to 1
0,0/1,1
*
BLDR  B VARIABLE (&LDRFLAG)AND(&LDRDOWN'E'PH10)
BDMP  B VARIABLE ((&CRSFLAG)AND(&CRSDOWN'E'PH10))OR((&WASFLAG)AND_
(&WASDOWN'E'PH10))
*
*****
***** MAIN SIMULATION MODEL *****
*****
SIMULATE
RMULT      12345

```

```

REALLOCATE COM,1000000
DO      &X=1,&DATA1(3)+&DATA1(4)          'Defining storage space for dumps
STORAGE      S(ML(DINFO,&X,1)),ML(DINFO,&X,2)
ENDDO

TRUCK GENERATE 1,0.1,0,&DATA1(1),,20PH,12PL,2PF  'Each Tx generated : 1 min +-0.1
ASSIGN      1,N(TRUCK),PH                'PH1 reserved for Tx no/ Hauler no
*

BLET  PL6=0          'Informing to DISPATCH, it is start of simulation
BLET  PH11=2         'informing to DISPATCH, this hauler is going to loaders
TRANSFER      SBR,DSPATCH,7PH          'calling DISPATCH
BLET  PL6=1          'PL6=1 for rest of the simulation
*

SEIZE  55000          'Max facility no taken in memory
RELEASE      55000
*

***** Check: Is this Tx (Hauler) for Ore or for Waste ? *****
*

BLET  PH3=ML(LINFO,PH13,2)      'If Ore-loader, PH3=1; if Waste-loader, PH3=2
BLET  PH3=PH3+30                ' PH3=31 for empty ore, 32 for empty waste
*

***** Initiating : Putting TxS (Haulers) on their respective Loaders *****
*

TRANSFER      SBR,INVPATH,7PH      'Transfer to sub-routine (INVPATH)
BPUTPIC FILE=OUTANIM,LINES=4,AC1,PH3,PH1,PH1,PH4,PH3,PH1+100
TIME *,***
CREATE Trk* *
PLACE * ON P* AT END
CREATE Trk* *

BLET  ML(H1OUT,PH1,1)=0          'initializing utilization of each hauler=0
BLET  ML(H1OUT,PH1,5)=-0.5       'initializing no of cycles
*

***** Starting the Cycle : Putting TxS (haulers) in Queue at respective loaders *****
*

UPTO  QUEUE PH13                'Queue at own loader - checked from RINFO
TRANSFER      SBR,HLRFail,7PH      'Transfer to HLRFAIL to check failure
BLET  ML(H1OUT,PH1,5)=ML(H1OUT,PH1,5)+0.5      'incrementing no of cycles
BLET  ML(H1OUT,PH1,7)=1.0         'setting wait flag to 1
SEIZE  PH13                      'Seize the loader
DEPART      PH13                  'if loader is free, depart the queue

```

```

        BLET    ML(H1OUT,PH1,7)=0.0                'setting wait flag to 0
FINDLD BLET    PL8=RVNORM(1,ML(HLOAD,PH1,PH13),ML(HLOAD,PH1,PH13)/10.0)
        TEST    LE PL8,ML(HINFO,PH1,1)+(ML(HINFO,PH1,1)/10.0),FINDLD
        BLET    ML(LOCOUT,PH13,1)=ML(LOCOUT,PH13,1)+PL8    'Cumulative Production
        BLET    ML(LOCOUT,PH13,4)=ML(LOCOUT,PH13,4)-ML(HLOAD,PH1,PH13)
        BLET    ML(H2OUT,PH1,PH13)=ML(H2OUT,PH1,PH13)+PL8    'Cumulative entries
        BLET    PL1=(RVNORM(1,ML(HLTIME,PH1,PH13),ML(HLTIME,PH1,PH13)/10.0))/_
(&DATA2(1)/100)                'PL1 for loader time with op efficiency accounted
        BPUTPIC FILE=OUTANIM,LINES=2,AC1,PH1,PL1/4,ML(LINFO,PH13,6),_
ML(LINFO,PH13,7)
TIME *,***
MOVE *,*** **
        ADVANCE    PL1*3.0/4.0    'Time to move: 1/4 & time to work at loader: 2/4
        BLET    PH3=ML(LINFO,PH13,2)    'Haulers are filled, so PH3 reduced to 1 or 2
        BPUTPIC FILE=OUTANIM,LINES=4,AC1,PH1,PH3,PH1,PL1/4,_
ML(LINFO,PH13,4),ML(LINFO,PH13,5),PH1+100,PH3
TIME *,***
SET * CLASS Trk*
MOVE *,*** **
SET * CLASS Trk*
        ADVANCE    PL1/4.0    'Time to move back to path: 1/4 of loader time
        RELEASE    PH13    'Release the facility (The Loader)
*
        BLET    PH11=1    'informing DISPATCH, this hauler is going to dump
        TRANSFER    SBR,DISPATCH,7PH    'calling DISPATCH
*
***** MOVING THROUGH ROAD SECTIONS - LOADER TO
CRUSHER (CRS) / WASTE DUMP (WAS) *****
*
        BLET    PH2=1    'incremental for road sections (initialize with 1st road section)
BACK TEST    NE MH(RLENGTH,PH9,PH2),0,DOWN    'check if length is not zero
        TEST    E ML(HSL,PH2,ML(HINFO,PH1,4)), -1,CORSP    'If user mentioned 'H' (-1)
        BLET    PL2=(0.06*MH(RLENGTH,PH9,PH2))/ML(HINFO,PH1,2)    '...calc time
        TRANSFER    ,INCORSP
CORSP BLET    PL2=(0.06*MH(RLENGTH,PH9,PH2))/ML(HSL,PH2,_
ML(HINFO,PH1,4))    '...otherwise calc time from formula
INCORSP BLET    PL2=(RVNORM(1,PL2,PL2/10.0))/(&DATA2(1)/100)
        BLET    PH4=MH(RPATH,PH9,PH2)    'PH4 is original path no (e.g. 1 or 101)
        BPUTPIC FILE=OUTANIM,LINES=3,AC1,PH1,PH4,PH1,PL2

```

TIME *.***

PLACE * ON P*

SET * TRAVEL *.***

***** MOVING THROUGH RD SEMENTS *****

```
TEST   G PH4,100,GO1           'check if its dir is forward or reverse ?
BLET   PF1=(PH4*500)-20499      'PF1 is start road segment (if PH4>100)
TRANSFER    ,GO4
GO1    BLET   PF1=(PH4*500)-399  'PF1 is the start road segment (if PH4<100)
GO4    BLET   PF2=PF1+(MH(RLENGTH,PH9,PH2)/30.0)-1  'PF2 is end road segment
        BLET   PH8=1            'PH8 is path segment no
GO3    TEST   LE PF1,PF2,GO2     'start incrementing the road segments
TRANSFER    SBR,HLRFAIL,7PH     'Transfer to HLRFAIL to check failure
        SEIZE  PF1              'seize each segment...
        ADVANCE    30*(PL2/MH(RLENGTH,PH9,PH2))      '...for the required time
        RELEASE    PF1          '...then release this segment
        BLET   PF1=PF1+1        'increment for next road
        BLET   PH8=PH8+1        'increment for next road segment
        BLET   ML(H1OUT,PH1,3)=ML(H1OUT,PH1,3)+0.03 'dist-loaded (in kms)=30 m
TRANSFER    ,GO3
GO2    TEST   NE FLT(MH(RLENGTH,PH9,PH2)@30.0),0,GOJUNC
        BLET   PH5=MH(RLENGTH,PH9,PH2)-((PH8-1)*30)  'PH5 is the left over dist
TRANSFER    SBR,HLRFAIL,7PH     'Transfer to HLRFAIL
        SEIZE  PF1              'seize the segment...
        ADVANCE    PH5*(PL2/MH(RLENGTH,PH9,PH2))      '...for the required time
        RELEASE    PF1          '...then release this segment
        BLET   ML(H1OUT,PH1,3)=ML(H1OUT,PH1,3)+FLT(PH5/1000.0)
```

*

***** Check for Junctions *****

```
GOJUNC    BLET   PH2=PH2+1      'increment for next road section
        TEST   NE MB(RJUNC,PH9,PH2),0,NEXTRD  'check if junction is there
TRANSFER    SBR,HLRFAIL,7PH     'Transfer to HLRFAIL
        SEIZE  MB(RJUNC,PH9,PH2)  'seize junction if it is there
        ADVANCE    &DATA2(10)    'junction delay
        RELEASE    MB(RJUNC,PH9,PH2)  'release junction
NEXTRD    TRANSFER    ,BACK      'Go BACK to repeat for next road section
```

*

***** ON THE CRUSHER (CRS) / WASTE DUMP (WAS) *****

*

```

DOWN QUEUE PH14                                'Queue at crusher (Crs)/ Waste Dump (Was)
TRANSFER    SBR,HLRFail,7PH                    'Transfer to HLRFAIL
BLET  ML(H1OUT,PH1,5)=ML(H1OUT,PH1,5)+0.5      'incrementing no of cycles
BLET  ML(H1OUT,PH1,7)=1.0                      'setting wait flag to 1
ENTER PH14                                     'Enter any dump point if available
DEPART      PH14                               'Depart the queue
BLET  ML(H1OUT,PH1,7)=0.0                      'setting wait flag to 0
BLET  ML(H3OUT,PH1,PH14-&DATA1(2))=ML(H3OUT,PH1,_
PH14-&DATA1(2))+PL8                             'Cumulative production at dump wrt hauler
BLET  ML(LOCOUT,PH14,1)=ML(LOCOUT,PH14,1)+PL8
BLET  ML(LOCOUT,PH14,2)=ML(LOCOUT,PH14,2)+1    'Cumulative Hauler entries
BLET  ML(LOCOUT,PH14,4)=ML(LOCOUT,PH14,4)-PL8
BLET  PL3=(RVNORM(1,ML(DINFO,PH14-&DATA1(2),8),ML(DINFO,_
PH14-&DATA1(2),8)/10.0))/(&DATA2(1)/100)      'Time at Crs/Was normalized
BPUTPIC FILE=OUTANIM,LINES=2,AC1,PH1,PL3/4,_
ML(DINFO,PH14-&DATA1(2),6),ML(DINFO,PH14-&DATA1(2),7)
TIME *.***
MOVE *.*** *
ADVANCE     PL3*3.0/4.0                        'Time to move: 1/4 & time to work at dump: 2/4
*
BLET  PH11=2                                  'informing DISPATCH, hauler is going to loader
TRANSFER    SBR,DSPATCH,7PH                    'calling DISPATCH
*
BLET  PH3=ML(LINFO,PH13,2)+30                  'Right now haulers are made empty
BPUTPIC FILE=OUTANIM,LINES=4,AC1,PH1,PH3,PH1,PL3/4,_
ML(DINFO,PH14-&DATA1(2),4),ML(DINFO,PH14-&DATA1(2),5),PH1+100,PH3
TIME *.***
SET * CLASS Trk*
MOVE *.*** *
SET * CLASS Trk*
ADVANCE     PL3/4.0                            'Time to move to path: 1/4 of Crs/Was time
LEAVE PH14                                     'Leave the dump point and storage
*
***** MOVING BACK – CRUSHER (CRS) / WASTE
DUMP (WAS) TO LOADER *****
*
BLET  PH2=MH(RINFO,PH9,3) 'incremental for road section
BACK2 TEST NE PH2,0,DOWN2                      'check if road section >0 (decrementing from largest)
TEST  E ML(HSE,PH2,ML(HINFO,PH1,4)), -1,CORS1  'If user mentioned 'H'

```

```

        BLET  PL4=(0.06*MH(RLENGTH,PH9,PH2))/ML(HINFO,PH1,3)  '...calc time
TRANSFER    ,INCORS1
CORS1 BLET  PL4=(0.06*MH(RLENGTH,PH9,PH2))/ML(HSE,PH2,ML(HINFO,PH1,4))
INCORS1      BLET  PL4=(RVNORM(1,PL4,PL4/10.0))/(&DATA2(1)/100)
        BLET  PH4=MH(RPATH,PH9,PH2)      'PH4 is original path no (e.g. 1 or 101)
        TEST  G PH4,100,DOWN3            'Correcting PH4 for the return
        BLET  PH4=PH4-100
        BLET  PF1=(PH4*500)-399          'PF1 the start road segment (for PH4<100)
TRANSFER    ,DOWN4
DOWN3      BLET  PH4=PH4+100
        BLET  PF1=(PH4*500)-20499        'PF1 is start road segment (for PH4>100)
DOWN4      BPUTPIC FILE=OUTANIM,LINES=3,AC1,PH1,PH4,PH1,PL4
TIME *,***
PLACE * ON P*
SET * TRAVEL *,***
*****
*** MOVING THROUGH ROAD SEGMENTS *****
        BLET  PF2=PF1+(MH(RLENGTH,PH9,PH2)/30.0)-1      'PF2 is end road segment
        BLET  PH8=1      'PH8 is path segment no
GO6  TEST  LE PF1,PF2,GO5      'start incrementing the road
        TRANSFER  SBR,HLRFAIL,7PH      'Transfer to HLRFAIL
        SEIZE  PF1      'seize each segment...
        ADVANCE  30*(PL4/MH(RLENGTH,PH9,PH2))      '...for the required time
        RELEASE  PF1      '...then release this segment
        BLET  PF1=PF1+1      'increment for next road segment
        BLET  PH8=PH8+1
        BLET  ML(H1OUT,PH1,4)=ML(H1OUT,PH1,4)+0.03      'dist-empty (in kms)=30m
TRANSFER    ,GO6
GO5  TEST  NE FLT(MH(RLENGTH,PH9,PH2)@30.0),0.0,GOJUNC1
        BLET  PH5=MH(RLENGTH,PH9,PH2)-((PH8-1)*30)      'PH5 is the left over dist
        TRANSFER  SBR,HLRFAIL,7PH      'Transfer to HLRFAIL
        SEIZE  PF1      'seize the segment...
        ADVANCE  PH5*(PL4/MH(RLENGTH,PH9,PH2))      '...for the required time
        RELEASE  PF1
        BLET  ML(H1OUT,PH1,4)=ML(H1OUT,PH1,4)+FLT(PH5/1000.0)
*
*****
***** Check for Junctions *****
GOJUNC1  TEST  NE MB(RJUNC,PH9,PH2),0,NEXTRD1      'check if junction is there

```

```

TRANSFER    SBR,HLRFAIL,7PH      'Transfer to HLRFAIL
SEIZE  MB(RJUNC,PH9,PH2)          'seize junction if it is there
ADVANCE      &DATA2(10)            'junction delay
RELEASE      MB(RJUNC,PH9,PH2)     'release junction
NEXTRD1      BLET  PH2=PH2-1        'Decrement for next road
TRANSFER      ,BACK2              'Go BACK to repeat for next road section
*
DOWN2        TRANSFER    ,UPTO      'Tx reached back; repeat the whole cycle
*
***** INVERT PATH SUBROUTINE *****
INVPATH      BLET  PH8=MH(RLENGTH,PH9,1)/30  'PH8 is path segment no
              BLET  PH4=MH(RPATH,PH9,1)      'PH4 used for original path number
              TEST  G PH4,100,MOV3
              BLET  PH4=PH4-100
              TRANSFER    ,PH7+1
MOV3  BLET  PH4=PH4+100
              TRANSFER    ,PH7+1
***** DISPATCH SUBROUTINE *****
DSPATCH      TEST  E &DATA1(10),1,FIXD      ' check for variable (1) or fixed (0)
              TRANSFER    ,TOLDRS
TOLDRS      TEST  E PH11,2,TODMPS            'if the hauler is going to loaders
              BLET  PH10=1                    'PH10 used for looping here
MLPR1  TEST  LE PH10,&DATA1(2),MLPR2          'Filling MLPR check no
*****Formula for MLPR check no
              BLET  ML(LOCOUT,PH10,3)=(AC1*ML(LINFO,PH10,3)/_
(&DATA1(5)*&DATA1(6)))-(ML(LOCOUT,PH10,1)+ML(LOCOUT,PH10,4))
              BLET  PH10=PH10+1
              TRANSFER    ,MLPR1
MLPR2  BLET  PH10=1                          'PH10 used for looping here
**if there is only one loader, either it fails or not haulers will be dispatched to it
              TEST  E PH10,&DATA1(2),MLPR6
              BLET  PH12=PH10                  'PH12 (dummy) is the loader no
              TRANSFER    ,MLPR3
**if there is more than 1 loader available, come here
MLPR6  TEST  LE PH10,&DATA1(2),MLPR3          'Checking the max MLPR check no
              TEST  E PH10,1,MLPR4
**If 1st loader fails, choose the 2nd loader to initialize the value of PL5
              TEST  E BV(BLDR),1,MLPR06        'if the checked loader is down
              BLET  PH10=PH10+1                '...set initial PH10 to next loader no

```


MLPR06 BLET PL5=ML(LOCOUT,PH10,3) 'PL5 used to store max MLPR no
 BLET PH12=PH10 'PH12 (dummy) is the loader no
 TRANSFER ,MLPR5

**if second onward Loader fails

MLPR4 TEST E BV(BLDR),1,MLPR07 'if the checked loader is down

**if it's not the last loader

 TEST NE PH10,&DATA1(2),MLPR3
 BLET PH10=PH10+1

MLPR07 TEST G ML(LOCOUT,PH10,3),PL5,MLPR5
 BLET PL5=ML(LOCOUT,PH10,3) 'PL5 used to store max MLPR no
 BLET PH12=PH10 'PH12 (dummy) is the loader no

MLPR5 BLET PH10=PH10+1
 TRANSFER ,MLPR6

**when PH12 is finalized then come here

MLPR3 BLET ML(LOCOUT,PH12,4)=ML(LOCOUT,PH12,4)+_
 (ML(HLOAD,PH1,PH12)) 'Storing production of en-route hauler in LOCOUT matrix

 BLET PH10=0 'PH10 used for looping here
 TEST E PL6,0,MLPR7 'checking is it start of simulation ?

MLPR8 BLET PH10=PH10+1
 TEST LE PH10,&DATA1(8),MLPREND 'loop until <=RINFO Row no
 TEST E MH(RINFO,PH10,1),PH12,MLPR8 'finding loader in RINFO column 1
 BLET PH9=PH10 'PH9=RINFO Row No
 TRANSFER ,MLPREND

MLPR7 BLET PH10=PH10+1 'If it is not start of Simulation!
 TEST LE PH10,&DATA1(8),MLPREND 'loop until <=RINFO Row no
 TEST E MH(RINFO,PH10,1),PH12,MLPR7 'finding loader in RINFO column 1
 TEST E MH(RINFO,PH10,2),MH(RINFO,PH9,2),MLPR7
 BLET PH9=PH10 'Assigned PH9=RINFO Row No

MLPREND BLET PH13=PH12 'PH13=Loader no
 TRANSFER ,PH7+1

*

***** MLPR To Dumps *****

*

TODMPS TEST E PH3,1,MLPR00 'if hauler exiting from Ore Loader
 BLET PH15=&DATA1(2)+1 'PH15: Start row in LOCOUT
 BLET PH16=&DATA1(2)+&DATA1(3) 'PH16: and End row in LOCOUT
 TRANSFER ,MLPR01

MLPR00 BLET PH15=&DATA1(2)+&DATA1(3)+1 'If hauler exiting from Was-loader
 BLET PH16=&DATA1(2)+&DATA1(3)+&DATA1(4)

MLPR01 BLET PH10=PH15 'PH10 used for looping here

MLPR11 TEST LE PH10,PH16,MLPR21 'Looping till end row (PH16)

*****Formula for MLPR

 BLET ML(LOCOUT,PH10,3)=(AC1*ML(DINFO,PH10-&DATA1(2),3)/_

(&DATA1(5)*&DATA1(6)))-(ML(LOCOUT,PH10,1)+ML(LOCOUT,PH10,4))

 BLET PH10=PH10+1

 TRANSFER ,MLPR11

MLPR21 BLET PH10=PH15 'PH10 used for looping here

**if there is only one Dump, either it fails or not haulers will be dispatched to it

 TEST E PH10,PH16,MLPR61

 BLET PH12=PH10 'PH12 (dummy) is the loader no

 TRANSFER ,MLPR31

**if there are more than 1 Dumps available, come here

MLPR61 TEST LE PH10,PH16,MLPR31 'Checking max MLPR check no

 TEST E PH10,PH15,MLPR41 'Storing PL5=1st Dump's MLPR no

**If 1st Dump fails, choose the 2nd Dump to initialize the value of PL5

 TEST E BV(BDMP),1,MLPR62 'if the checked Dump is down

 BLET PH10=PH10+1

MLPR62 BLET PL5=ML(LOCOUT,PH10,3) 'PL5 used to store max MLPR no

 BLET PH12=PH10 'PH12 (dummy) is the dump

 TRANSFER ,MLPR51

**if 2nd onward Dump fails

MLPR41 TEST E BV(BDMP),1,MLPR72 'if the checked Dump is down

**if it's not the last loader

 TEST NE PH10,PH16,MLPR31

 BLET PH10=PH10+1

MLPR72 TEST G ML(LOCOUT,PH10,3),PL5,MLPR51

 BLET PL5=ML(LOCOUT,PH10,3) 'PL5 used to store max MLPR no

 BLET PH12=PH10 'PH12 (dummy) is the dump no

MLPR51 BLET PH10=PH10+1

 TRANSFER ,MLPR61

**when PH12 is finalized then come here

MLPR31 BLET ML(LOCOUT,PH12,4)=ML(LOCOUT,PH12,4)+PL8

 BLET PH10=0 'PH10 used for looping here

MLPR71 BLET PH10=PH10+1 'If it is not start of simulation!

 TEST LE PH10,&DATA1(8),MLPREN1 'loop until <=RINFO Row nos

 TEST E MH(RINFO,PH10,2),PH12,MLPR71 'finding loader in RINFO column 1

 TEST E MH(RINFO,PH10,1),MH(RINFO,PH9,1),MLPR71

 BLET PH9=PH10 'Assigned new PH9=RINFO Row No

```

MLPREN1      BLET  PH14=PH12
              TRANSFER  ,PH7+1          'PH14=Dump no to which hauler is assigned
*
***** FIXED ALLOCATION *****
*
FIXD  TRANSFER  ,FTOLDR
FTOLDR      TEST  E PH11,2,FTODMP      'if hauler is going towards loaders (PH11=2)
              BLET  PH9=ML(HINFO,PH1,5)
              BLET  PH13=MH(RINFO,PH9,1)
              TRANSFER  ,PH7+1
***** FIXED ALLOCATION - TO DUMPS *****
FTODMP      BLET  PH9=ML(HINFO,PH1,5)
              BLET  PH14=MH(RINFO,PH9,2)
              TRANSFER  ,PH7+1
*
***** CHECK HAULER DOWN SUBROUTINE (ON THE
ROAD NETWROK) *****
HLRFAIL      TEST  E PH1,&HLRDOWN,PH7+1      'if failed hauler is equal to current Tx
              TEST  E &HLRFLAG,1,PH7+1      'if this hauler has failed
              BLET  &HFNO=&HFNO+1
              BLET  PL9=AC1
              BPUTPIC FILE=OUTANIM,LINES=4,AC1,PH1,PH3,PH1,PH1+100,PH3
TIME *.***
SET * CLASS TrkF*
MOVE * 0.001 0 0 relative
SET * CLASS TrkF*
              BPUTPIC
FILE=OUTANIM,LINES=3,PH3,&HFNO,&HFNO,640+((310/FLT(&DATA1(5)*_
&DATA1(6)))*AC1),&HFNO      'write info in ATF graph
CREATE TrkF* HF*
PLACE HF* AT *,* -60
WRITE HF1 H (*)
              BLET  ML(H1OUT,PH1,7)=1.0      'setting wait flag to 1
              TEST  E &HLRFLAG,0      'Halt the tx/ hauler for MTTR
              BLET  ML(H1OUT,PH1,7)=0.0      'setting wait flag to 0
              BLET  &HFTIME=&HFTIME+(AC1-PL9)
              BPUTPIC
FILE=OUTANIM,LINES=5,AC1,PH1,PH3,PH1,PH4,30*600*PH8/&DATA1(7),_
&HFTIME,PH1+100,PH3

```

```

TIME *.***
SET * CLASS Trk*
PLACE * on P* at *.*
WRITE HF2 * m
SET * CLASS Trk*

TRANSFER      ,PH7+1

*****
***** LOADER DOWN *****

GENERATE ,,,1,,2PH,2PL                                'Dummy Tx
DOSTOP1      BLET  PH1=FIX((FN(RNDNO)*&DATA1(2))+1)
BLET  &LDRDOWN=PH1                                     'Loader no to fail next
BLET  PH2=0
BLET  &LDRFLAG=PH2                                     'Set LDRFLAG to 0 (Loader ok)
BLET  PL1=RVEXPO(1,&DATA2(2))                          'MTBF Of Loaders
BLET  PL2=RVNORM(1,&DATA2(3),&DATA2(3)/10.0)            'MTTR of Loaders
ADVANCE      PL1                                       'Let the Loaders work for MTBF
BLET  PH2=1
BLET  &LDRFLAG=PH2
'Set the LDRFLAG to 1 (Loader failed)
FUNAVAIL PH1                                           'Loader no more available
ADVANCE PL2                                           'Let down Loader repair for MTTR
FAVAIL      PH1                                       'Loader is available onwards
TRANSFER      ,DOSTOP1

*****
***** CRUSHER DOWN *****

GENERATE ,,,1,,2PH,2PL                                'Dummy Tx
DOSTOP2      BLET  PH1=FIX((FN(RNDNO)*&DATA1(3))+1+&DATA1(2))
BLET  &CRSDOWN=PH1                                     'Crs no to fail next
BLET  PH2=0
BLET  &CRSFLAG=PH2                                     'Set the CRSFLAG to 0 (Crs ok)
BLET  PL1=RVEXPO(1,&DATA2(6))                          'MTBF Of Crs
BLET  PL2=RVNORM(1,&DATA2(7),&DATA2(7)/10.0)            'MTTR of Crs
TEST  G &DATA1(3),0                                  'if there is any Crs in mine
ADVANCE      PL1                                       'Let the Crs work for MTBF
BLET  PH2=1
BLET  &CRSFLAG=PH2                                     'Set the CRSFLAG to 1 (Crs failed)
SUNAVAIL PH1                                           'Dump no more available
ADVANCE PL2                                           'Let down dump repair in MTTR
SAVAIL      PH1                                       'Dump is available onwards

```

```

TRANSFER      ,DOSTOP2
*****
***** WASTE DUMP DOWN *****
      GENERATE ,,,1,,2PH,2PL                      'Dummy Tx
DOSTOP3      BLET
      PH1=FIX((FN(RNDNO)*&DATA1(4))+1+&DATA1(2)+&DATA1(3))
      BLET  &WASDOWN=PH1                          'Waste dump no to fail next
      BLET  PH2=0
      BLET  &WASFLAG=PH2                          'Set the WASFLAG to 0
      BLET  PL1=RVEXPO(1,&DATA2(8))                'MTBF Of Waste dump
      BLET  PL2=RVNORM(1,&DATA2(9),&DATA2(9)/10.0) 'MTTR of Waste dump
      TEST   G &DATA1(4),0                        'if there is any Was in mine
      ADVANCE   PL1                                'Let Waste dump work for MTBF
      BLET  PH2=1
      BLET  &WASFLAG=PH2                          'Set the WASFLAG to 1 (failed)
      SUNAVAIL PH1                                'Dump no more available
      ADVANCE PL2                                'Let down dump repair in MTTR
      SAVAIL      PH1                              'Dump is available onwards
      TRANSFER    ,DOSTOP3
*****
***** HAULER DOWN *****
      GENERATE ,,,1,,2PH,2PL                      'Dummy Tx
      BLET  PH1=1
DOSTOP4      BLET  PH1=FIX((FN(RNDNO)*&DATA1(1))+1)
      BLET  &HLRDOWN=PH1                          'Hauler no to fail next
      BLET  PH2=0
      BLET  &HLRFLAG=PH2                          'Set HLRFLAG to 0 (hauler ok)
      BLET  PL1=RVEXPO(1,&DATA2(4))                'MTBF Of HLR
      BLET  PL2=RVNORM(1,&DATA2(5),&DATA2(5)/10.0) 'MTTR of HLR
      ADVANCE   PL1                                'Let haulers work for MTBF
      BLET  PH2=1
      BLET  &HLRFLAG=PH2                          'Set HLRFLAG to 1(hauler failed)
      ADVANCE PL2                                'Let down HLR repair in MTTR
      TRANSFER    ,DOSTOP4
*****
***** CALCULATE HAULER WAITING TIME *****
      GENERATE ,,,1,,1PH                          'Dummy Tx
      WHLR BLET  PH1=1
      WHLR1 TEST  LE PH1,&DATA1(1),WHLR3

```

```

TEST  E ML(H1OUT,PH1,7),1.0,WHLR2
BLET  ML(H1OUT,PH1,6)=AC1
BLET  ML(H1OUT,PH1,7)=2.0
WHLR2 BLET  PH1=PH1+1
      TRANSFER      ,WHLR1
WHLR3 ADVANCE      0.016666
      BLET  PH1=1
WHLR4 TEST  LE PH1,&DATA1(1),WHLR
      TEST  E ML(H1OUT,PH1,7),2.0,WHLR5
      BLET  ML(H1OUT,PH1,2)=ML(H1OUT,PH1,2)+(AC1-ML(H1OUT,PH1,6))
      BLET  ML(H1OUT,PH1,6)=AC1
WHLR5 BLET  PH1=PH1+1
      TRANSFER      ,WHLR4
*****
***** SHOW TIME, INFO IN ANIMATION, AND LOCATION FAIL *****
      GENERATE ,,1,,12PH,8PL      'Dummy Tx
      BLET  PH3=1      'PH3 Dedicated for LdrFail flag
      BLET  PH4=1      'PH4 Dedicated for CrsFail flag
      BLET  PH5=1      'PH5 Dedicated for WasFail flag
      BLET  PH7=1      'PH7 Dedicated to shift number
      BLET  PH8=0      'PH8 Dedicated to loader fail count
      BLET  PH9=0      'PH9 Dedicated to crusher fail count
      BLET  PH10=0     'PH10 Dedicated to waste fail count
      BPUTPIC FILE=OUTANIM,LINES=3,AC1,PH7      'write SHIFT & other info in atf
TIME *,***
WRITE SSHIFT *
CREATE MovLine ML1
      BLET  PH11=1      'PH11 used for looping to find ore & waste
PROD11      TEST  LE PH11,&DATA1(3),PROD22
      BLET  PL5=PL5+ML(DINFO,PH11,3)      'PL5 is the total ore TARGET prod
      BLET  PH11=PH11+1
      TRANSFER      ,PROD11
PROD22      BLET  PH11=&DATA1(3)+1      'PH11 used for looping to find ore & waste
PROD33      TEST  LE PH11,&DATA1(3)+&DATA1(4),PROD44
      BLET  PL6=PL6+ML(DINFO,PH11,3)      'PL6 is the total waste TARGET prod
      BLET  PH11=PH11+1
      TRANSFER      ,PROD33
PROD44      BPUTPIC
FILE=OUTANIM,LINES=2,0,PL5,&DATA1(5)*&DATA1(6),PL5,0,PL6,&DATA1(5)_

```

```

*&DATA1(6),PL6
plot PROD *.**.*.*.* color F7
plot PROD *.**.*.*.* color F4
*
*
TIME  BLET  PH11=1                      'PH11 used for looping to find hauler utilization
      BLET  PH12=-48
HUTIL TEST  NE AC1,0.0,HUTIL1          'To prevent division by zero
      TEST  LE PH11,&DATA1(1),HUTIL1
      TEST  NE ML(H1OUT,PH11,1),-1.0,HUTIL2      'To write in atf if hauler is created
      BLET  ML(H1OUT,PH11,1)=(AC1-ML(H1OUT,PH11,2))/AC1      '% Utilization
      BPUTPIC
FILE=OUTANIM,LINES=2,PH11,ML(H1OUT,PH11,1)*100.0,ML(H1OUT,PH11,3),_
ML(H1OUT,PH11,4),PH11+100,PH12
WRITE HLRINFO* ***,*   ***,**   ***,**
PLACE * AT -149 *.*
HUTIL2 BLET  PH11=PH11+1
      BLET  PH12=PH12-15
      TRANSFER      ,HUTIL
HUTIL1 BLET  PL5=0                      'PL5 is the total ore prod
      BLET  PL6=0                      'PL6 is the total waste prod
      BLET  PH11=&DATA1(2)+1          'PH11 used for looping to find ore & waste
PROD1 TEST  LE PH11,&DATA1(2)+&DATA1(3),PROD2
      BLET  PL5=PL5+ML(LOCOUT,PH11,1)
      BLET  PH11=PH11+1
      TRANSFER      ,PROD1
PROD2 BLET  PH11=&DATA1(2)+&DATA1(3)+1
PROD3 TEST  LE PH11,&DATA1(2)+&DATA1(3)+&DATA1(4),PROD4
      BLET  PL6=PL6+ML(LOCOUT,PH11,1)
      BLET  PH11=PH11+1
      TRANSFER      ,PROD3
PROD4 BPUTPIC FILE=OUTANIM,LINES=6,AC1,FIX(AC1/60),AC1@60,FIX(PL1/60),_
PL1@60,640+((310/FLT(&DATA1(5)*&DATA1(6)))*AC1),_
AC1-0.5,PL7,AC1,PL5,AC1-0.5,PL8,AC1,PL6
TIME *.***
WRITE STIME **.*
WRITE STIME1 **.*
PLACE ML1 AT *.* -175
plot PROD *.**.*.*.* color F7

```

```

plot PROD *.**.*.*.*.* color F4

      BLET   PL1=AC1-((PH7-1)*&DATA1(5))          'PL1 is the running time of shift
      TEST   GE PL1,&DATA1(5),NEXT1
      BLET   PH7=PH7+1
      BPUTPIC FILE=OUTANIM,LINES=1,PH7            'write SHIFT info in atf
WRITE SSHIFT *
NEXT1 BLET   PL7=PL5                                'PL7 used to store previous ore production
      BLET   PL8=PL6                                'PL8 used to store previous waste production
      BLET   PH2=1                                    'PH2 used for INFO looping
INFO  TEST   LE PH2,&DATA1(2),INFO1                'writing/ showing loader details
      BPUTPIC FILE=OUTANIM,LINES=1,PH2,FR(PH2)/10,QA(PH2),Q(PH2),QM(PH2),_
F(PH2),FC(PH2),ML(LOCOUT,PH2,1)
WRITE LDRINFO* **.* **.* **(**)      *(1)      *****
INFO1 TEST   LE PH2,&DATA1(3),INFO2                'writing/showing crusher details
      BPUTPIC
FILE=OUTANIM,LINES=1,PH2,SR(&DATA1(2)+PH2)/10,QA(&DATA1(2)+PH2),_
Q(&DATA1(2)+PH2),QM(&DATA1(2)+PH2),S(&DATA1(2)+PH2),_
SM(&DATA1(2)+PH2),SC(&DATA1(2)+PH2),ML(LOCOUT,&DATA1(2)+PH2,1)
WRITE CRSINFO* **.* **.* **(**)      *(*)      *****
INFO2 TEST   LE PH2,&DATA1(4),INFO3                'writing/showing waste details
      BPUTPIC
FILE=OUTANIM,LINES=1,PH2,SR(&DATA1(2)+&DATA1(3)+PH2)/10,QA(&DATA1(2)+_
+&DATA1(3)+PH2),Q(&DATA1(2)+&DATA1(3)+PH2),_
QM(&DATA1(2)+&DATA1(3)+PH2),S(&DATA1(2)+&DATA1(3)+PH2),SM(&DATA1(2)+_
+&DATA1(3)+PH2),SC(&DATA1(2)+&DATA1(3)+PH2),_
ML(LOCOUT,&DATA1(2)+&DATA1(3)+PH2,1)
WRITE WASINFO* **.* **.* **(**)      *(*)      *****
INFO3 BLET   PH2=PH2+1                                'incrementing looping PH2
      TEST   LE PH2,&DATA1(2)+&DATA1(3)+&DATA1(4),INFO4
      TRANSFER    ,INFO                                'Go up to INFO
*
*
***** SHOWING LDR FAIL IN ANIMATION *****
INFO4 TEST E &LDRFLAG,1,MOV4                        'check if ldrflag is set to 1
      TEST E PH3,1,MOV4                                'check if it's coming for 1st time
      BLET   PH6=&LDRDOWN                                'PH6 = LDR No which is down
      BLET   PH8=PH8+1                                    'PH8 Dedicated to loader fail count
      BLET   PL2=AC1                                    'PL2 used to record time of LDR failure

```



```

BPUTPIC
FILE=OUTANIM,LINES=5,ML(LINFO,PH6,6),ML(LINFO,PH6,7),ML(LINFO,PH6,2),_
PH8,PH8,640+((310/FLT(&DATA1(5)*&DATA1(6)))*AC1),PH8
CREATE FailLoc FailLdr
PLACE FailLdr AT * *
CREATE TrkF3* LF*
PLACE LF* AT *,* -90
WRITE LF1 L (*)
        BLET  PH3=0          'setting PH3=0, so simulation does not come in again here
*
MOV4  TEST E &LDRFLAG,0,MOV7          'if ldrflag set to zero from one
        TEST E PH3,0,MOV7          '... and PH3 is set to zero
        BLET  &LFTIME=&LFTIME+(AC1-PL2)
        BPUTPIC FILE=OUTANIM,LINES=2,&LFTIME  'destroy the cross sign of animation
DESTROY FailLdr
WRITE LF2 * m
        BLET  PH3=1
*
***** SHOWING Crusher FAIL IN ANIM *****
MOV7  TEST E &CRSFLAG,1,MOV8          'check if CRSFLAG is set to 1
        TEST E PH4,1,MOV8          'check if it's coming for 1st time
        BLET  PH6=&CRSDOWN          'PH6 = CRS No which is down
        BLET  PH9=PH9+1          'PH9 Dedicated for CRS fail count
        BLET  PL3=AC1          'PL3 used to record time of CRS failure
        BPUTPIC FILE=OUTANIM,LINES=5,ML(DINFO,PH6-&DATA1(2),6),ML(DINFO,_
PH6-&DATA1(2),7),PH9,PH9,640+((310/FLT(&DATA1(5)*&DATA1(6)))*AC1),PH9
CREATE FailLoc FailDmp
PLACE FailDmp AT * *
CREATE TrkF31 CF*
PLACE CF* AT *,* -120
WRITE CF1 C (*)
        BLET  PH4=0          'setting PH4=0, so simulation does not come in again here
*
MOV8  TEST E &CRSFLAG,0,MOV11          'if CRSFLAG set to zero from one
        TEST E PH4,0,MOV11          '... and PH4 is set to zero
        BLET  &CFTIME=&CFTIME+(AC1-PL3)
        BPUTPIC FILE=OUTANIM,LINES=2,&CFTIME  'destroy the cross sign of animation
DESTROY FailDmp
WRITE CF2 * m

```

```

        BLET   PH4=1
*
***** SHOWING WASTE DUMP FAIL IN ANIM *****
MOV11 TEST E &WASFLAG,1,MOV12           'check if WASFLAG is set to 1
      TEST E PH5,1,MOV12                 'check if it is coming for 1st time
      BLET   PH6=&WASDOWN                 'PH6 = WAS No which is down
      BLET   PH10=PH10+1                 'PH10 dedicated for WAS fail count
      BLET   PL4=AC1                     'PL4 used to record time of WAS failure
      BPUTPIC FILE=OUTANIM,LINES=5,ML(DINFO,PH6-&DATA1(2),6),ML(DINFO_
,PH6-&DATA1(2),7),PH10,PH10, 640+((310/FLT(&DATA1(5)*&DATA1(6)))*AC1),PH10
CREATE FailLoc FailDmp1
PLACE FailDmp1 AT * *
CREATE TrkF32 WF*
PLACE WF* AT *,* -150
WRITE WF1 W (*)
      BLET   PH5=0                       'setting PH5=0, so simulation does not come in again here
*
MOV12 TEST E &WASFLAG,0,MOV13           'if WASFLAG set to zero from one
      TEST E PH5,0,MOV13                 '... and PH5 is set to zero
      BLET   &WFTIME=&WFTIME+(AC1-PL4)
      BPUTPIC FILE=OUTANIM,LINES=2,&WFTIME 'destroy the cross sign of animation
DESTROY FailDmp1
WRITE WF2 * m
      BLET   PH5=1
*
MOV13 ADVANCE      0.5                   'update time = 0.5 min
      TRANSFER      ,TIME                 'Re-start the whole cycle
*
*****
***** TIMER TRANSACTION *****
      GENERATE      ,,1                   'Dummy Tx
      ADVANCE        &DATA1(5)*&DATA1(6) 'Simulation time x no of shifts
      TERMINATE      1
      START          1
*
      DO &X=1,&DATA1(2)+&DATA1(3)+&DATA1(4)
      IF      &X<=&DATA1(2)
      PUTPIC FILE=OUTFILE,LINES=1,&X,FR(&X)/10,FC(&X),FT(&X),QA(&X),_
ML(LOCOUT,&X,1)

```

```

***^***.^*****^***.^***.^***.^***
ELSE
    PUTPIC FILE=OUTFILE,LINES=1,&X,SR(&X)/10,SC(&X),ST(&X),QA(&X),_
ML(LOCOUT,&X,1)
***^***.^*****^***.^***.^***.^***
ENDIF
ENDDO
*
DO &X=1,&DATA1(1)
    PUTPIC FILE=OUTFILE,LINES=1,&X,ML(H2OUT,&X,1),ML(H2OUT,&X,2),_
ML(H2OUT,&X,3),ML(H2OUT,&X,4),ML(H2OUT,&X,5),ML(H2OUT,&X,6),_
ML(H2OUT,&X,7),ML(H2OUT,&X,8),ML(H2OUT,&X,9),ML(H2OUT,&X,10)
***^***.^***.^***.^***.^***.^***.^***.^***.^***.^***
ENDDO
DO &X=1,&DATA1(1)
    PUTPIC FILE=OUTFILE,LINES=1,&X,ML(H3OUT,&X,1),ML(H3OUT,&X,2),_
ML(H3OUT,&X,3),ML(H3OUT,&X,4),ML(H3OUT,&X,5),ML(H3OUT,&X,6),_
ML(H3OUT,&X,7),ML(H3OUT,&X,8),ML(H3OUT,&X,9),ML(H3OUT,&X,10)
***^***.^***.^***.^***.^***.^***.^***.^***.^***.^***
ENDDO
DO &X=1,&DATA1(1)
    PUTPIC FILE=OUTFILE,LINES=1,&X,ML(H1OUT,&X,1),ML(H1OUT,&X,2),_
ML(H1OUT,&X,3),ML(H1OUT,&X,4),ML(H1OUT,&X,5)
***^***.^***.^***.^***.^***.^***.^***.^***.^***.^***
ENDDO
PUTPIC FILE=OUTANIM,LINES=1
End
END

```

Electronic Version of the Simulation Software Program (CD)

1. General

This Appendix contains a CD which has two folders namely '*Installation*' and '*Videos*'. The setup files contained in the folder '*Installation*' installs the simulation software program on the computer. The user can use the complete program when the USB security key, having the license of GPSS/H and P5, is plugged in. The other folder '*Videos*' contains the video files that demonstrate the case studies of the chapter 6. The file names of the videos are '*Case_1.avi*', '*Case_2.avi*', '*Case_3_Scenario_A.avi*', and '*Case_3_Scenario_B.avi*'.

2. How to Install

The folder '*Installation*' has four files ('*1_Setup.exe*', '*2_Baseline_UL211.exe*', '*How_to_install.txt*', and '*Help.pdf*'). To install the simulation software program on the computer, follow the under mentioned steps:-

- **Step 1.** Double click the file '*1_Setup.exe*' that is contained in the folder '*installation*', and follow the on-screen instructions. It will install the program 'Simulation of Product Transportation in Open Pit Mines' on the computer, and will create a folder '*C:\Project*' on the C drive. The solved case studies of chapter 6 will be copied in the subfolder '*C:\Project\File*'. The user may use the software program after step 1; however the simulation and animation will not work until step 2 and 3 are done.
- **Step 2.** Double click the file '*2_Baseline_UL211.exe*' that is contained in the folder '*installation*', and follow the on-screen instructions. It will install the GPSS/H and P5 programs on the computer. It will also create a folder '*Wolverine*' on the computer desktop.
- **Step 3.** Make sure that the USB security key is plugged into the computer before performing step 3. Open the folder '*Wolverine*' that was created on the desktop during step 2, and double click the file '*Security Key Setup*'. Follow the on screen instructions to install the drivers of the security key.

After step 3, the user will also be able to view the simulation and animation outputs of the program (when the security key is plugged in).

3. How to Use

The file '*Help.pdf*' contained in the folder '*Installation*' provides the details on how to use the simulation program. The user can also access the file '*Help.pdf*' during the use of the program by clicking the '?' button provided on the program's main window.

4. How to Uninstall

Uninstall the following programs from the computer (by opening control panel/ programs and features):-

- Simulation of Product Transportation in Open Pit Mines Version 1.0
- Wolverine Software Products
- Sentinel Protection Installer 7.6.3