VALIDATION OF A DYNAMIC SIMULATION OF AN OPENCAST COAL MINE

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science 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 the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

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ABSTRACT

A dynamic simulation study is a critical deliverable of a mine project feasibility study. Mining houses rely on simulation to confirm that complex, integrated systems can achieve design capacity before investment decisions are made. Dynamic simulations are powerful tools, but only if they are developed using the right methodology, and with information that has been verified. The importance of work in the field of mine dynamic simulation validation was made clear during the early stages of this research report when it was identified that there is limited information available on the subject. Work conducted in the realm of validation can make an invaluable contribution to the success of future projects undertaken around the world.

The last few years have been difficult for employees of some mining companies because of looming job cuts due to high production costs, high overheads, and decreasing product demand. For many mining companies, it was a case of survival which gave rise to the development of new strategies and innovative thinking. Coal Mine A Life of Mine (LOM) extension project is a prime example of innovative thinking. In this case, the project was approved for implementation when export coal prices were on the low end of the price cycle. The dynamic simulation of the full materials handling value chain conducted during the project was of utmost importance, and provided assurance to the project review team that annual production targets can be achieved.

The simulation development methodology was based on a unique approach that reduced time spent on the simulation through the integration of different, independent models that represented sub-systems in the materials handling value chain. There was, therefore, a strong need to validate the simulation, which could lead to the adoption of this approach on future projects. In this research report, the LOM extension project scope and the mining activities conducted by Coal Mine A are explained, and a brief, but interesting history of Modelling and Simulation (M&S) is provided. The subject of M&S is vast and has evolved into its own separate discipline.

M&S is an invaluable tool, and the importance of verification, validation and credibility is elaborated on. The development of the simulation and the inputs and outputs of the simulation are discussed before the validation effort.

The work conducted on the validation aimed to confirm the accuracy of the simulation unequivocally. Although the production target was not achieved as predicted by the dynamic simulation during the period of validation, there was an indication that the materials handling value chain could perform as predicted as each of the individual sub-systems had achieved the design capacity. Problem areas were identified which could be attributed to the poor performance, and if these areas are addressed, the system could perform as predicted by the simulation. This confirms that dynamic simulation can add value to predictions about mining system performance such that informed decisions can be made.

ACKNOWLEDGEMENTS

I am indebted to my supervisor Prof. B. Genc for his support, dedication, commitment and constructive criticism during the development stages of this research report. I thank Johann Uys for his support and guidance during my studies. Lastly, I would like to thank my wife Anisha, my daughter Kendra, and my son Kian for their support and understanding during the many long hours I've put into this report.

DEDICATION

To Anisha, Kendra and Kian for all their love, patience and encouragement.

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LIST OF ACRONYMS AND ABBREVIATIONS

Ad……………………………..……………………………………….Air Dry

BMH………………………………...…….………Bulk Materials Handling

CBS………………………………………………..…Circular Blending System

CCR……………………………………….….Critical Constrained Resource

COT………………………………………….………Coaling Operating Time

DMS…………………………………….………..Dense Medium Separation

DOT……………………………………………..…..Direct Operating Time

FEL……………………………………………………...…..Front End Loader

FTP……………………………………………………...…….Feed to Plant

GPSS……………………………………General Purpose Simulation System

HME…………………………………….……………Heavy Mobile Equipment

HPGRs……………………………………..….…High Pressure Grinding Rolls

IRC……………………………………...…………Interactive Run Controller

Kt…………………………………………………………………..Kilo Tonnes

LOM……………………………………………………………………..Life of Mine

M&S……………………………………………………..Modelling and Simulation

MCRO……………………………...………Mine Control Room Operator

MIPS……………………..……...Method of Integrated Process Simulation

MJ/kg……………………………………………….………Megajoule per kg

MS……………………………………………………………………….Microsoft

MT………………………………………...…………….Million Tonnes

MTFF……………………………..………………...Mean Time To Failure

Mtpa……………………………………….…….Million Tonnes Per Annum

MTTR ……………………………………….…………Mean Time To Repair

NAR………………………………………………….……….Net as Received

PDF………………………………………...Probability Distribution Function

PERT…………………..……Programme Evaluation and Review Technique

PSD……………………………………….……..Particle Size Distribution

ROM………………………………………………….…………Run of Mine

SCADA……………………………Supervisory Control and Data Acquisition

t………………………………………………………………..……..Tonnes

TFR…………………………………….……………Transnet Freight Rail

THT…………………………………………..……….Train Handling Time

TLT…………………………………………………..……Train Loading Time

TOC…………………………………………….………Theory of Constraints

t/d…………………………………………………….………Tonnes per Day

t/h……………………………………..………………..Tonnes per Hour

vs……………………………………………………..…………Versus

1. INTRODUCTION

1.1 Background

The planned production which a mine is designed to deliver over the Life of Mine (LOM) is of utmost importance. The mine can suffer substantial losses if it does not deliver on production commitments documented in project feasibility studies. This research report is based on a mine designated herein as “Coal Mine A”, which had historically underperformed since its establishment in 2007. Coal Mine A is situated in the north-eastern part of South Africa, in the Mpumalanga province. The mine was designed to process 6 Million Tonnes (MT) of Run of Mine (ROM) from coal Resource 1 (Figure 1.1), and it had a LOM of approximately 11 years.

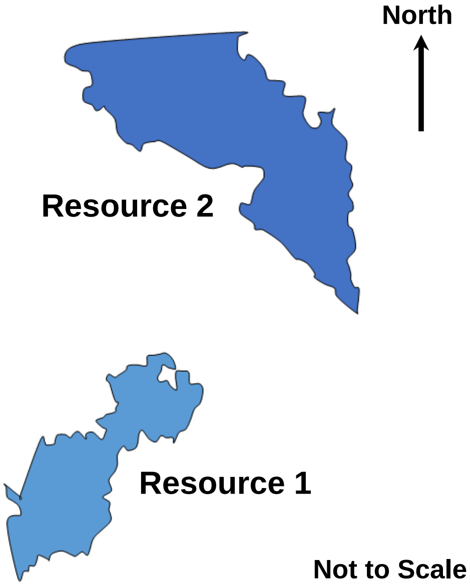


Figure 1.1: Coal Mine A Resources Proximity

Resource 2, located approximately 7 kilometres (km) away, was identified as a means of extending the LOM. The LOM extension project commenced in 2011 and has since been implemented. During the project study phases, various mining, coal transport, and mine infrastructure options were investigated. The go-forward option included the relocation of the mining equipment and the application of surface (terrace) mining processes.

1.2 Coal Mine A Mining Method

The outcome of an extensive mining options analysis was that the same mining method (Figure 1.2) used at Resource 1 be employed for the new mine (Resource 2).

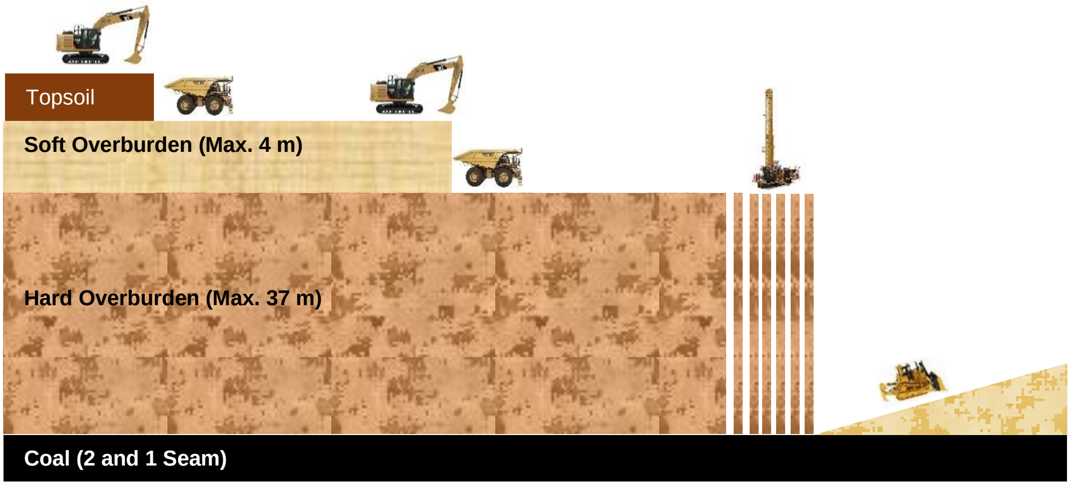
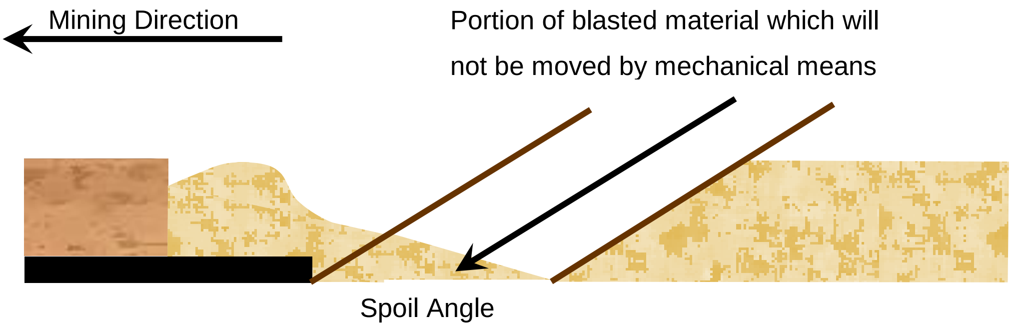


Figure 1.2: Mining Method

A boxcut or mining void needed to be constructed. Topsoil was stripped by contractors, to a maximum depth of 800 mm. The topsoil from the boxcut was planned to be stockpiled until the mine reaches steady state, after which direct placement of topsoil on levelled areas was planned. Overburden material from the boxcut was stockpiled outside the pit. The material regarded as soft overburden or "softs", which was ± 5 metres (m) above the hard overburden, was removed by excavators, and without the use of explosives. This material was generally placed on the levelled area immediately before the top soiling operation. All the remaining hard overburden, together with 5 m of soft material immediately above the hard material, was drilled and blasted in one pass, prior to excavation. Overburden removal was optimised using the cast blast technique. The blast gain efficiency of the cast blast was a measure of the volume of overburden thrown by the blast over the coal seam and was expressed as a factor of the total volume of the blast. At the original mine, the blast gain obtained at an overburden thickness of 20 m and a coal seam thickness of

5 m was 25%. Blast gain (Figure 1.3) was proven at the original mine to be the most cost-effective means of overburden removal as opposed to mechanical means. Blast volumes were maximised by limiting the soft material removed by truck and shovel (excavator) operations prior to the drilling operation.



Not to Scale

Figure 1.3: Blast Gain Schematic

To optimise the cast blast design and to create a stable highwall, the mine employed the use of pre-split drilling and blasting. This ensured that a competent vertical face was developed through to the floor of the lowest seam. The toe on the vertical face was required to be cleared which contributed to a smoother floor. This increased the efficiency of the blast gain. Post blasting of the hard overburden, track dozers were used to doze or push the overburden material, which is a technique referred to as rollover dozing. Dozing was conducted to push spoil material away from the highwall in a direction perpendicular to the mining strip’s direction (Figure 1.2).

The remainder of the hard overburden was removed using a truck and shovel operation. Thereafter, it was planned to drill and blast the coal seams and parting as single entities and mine each coal seam separately using trucks and shovels. The parting between 1 Seam and 2 Seam was removed either by dozers or an excavator. The parting was left in the pit or moved to an overburden stockpile area. The intention was to maintain no more than 10 strips before rehabilitation commenced. As the moving void progressed through the mining area, waste was dumped inside the void in areas where the coal seams had been removed. Topsoil was then placed on levelled areas.

1.3 Coal Mine A LOM Extension Project Scope

The project scope included the relocation of the ROM Tip and the construction of a new Bulk Materials Handling (BMH) system, which tied into the existing BMH system (Figure 1.4). The BMH system was an essential part of the overall system (Asbjörnsson et al., 2012). Infrastructure was relocated where possible or constructed new to support the mining processes. A project review team was appointed to conduct stage gate reviews at the end of each of the project phases.

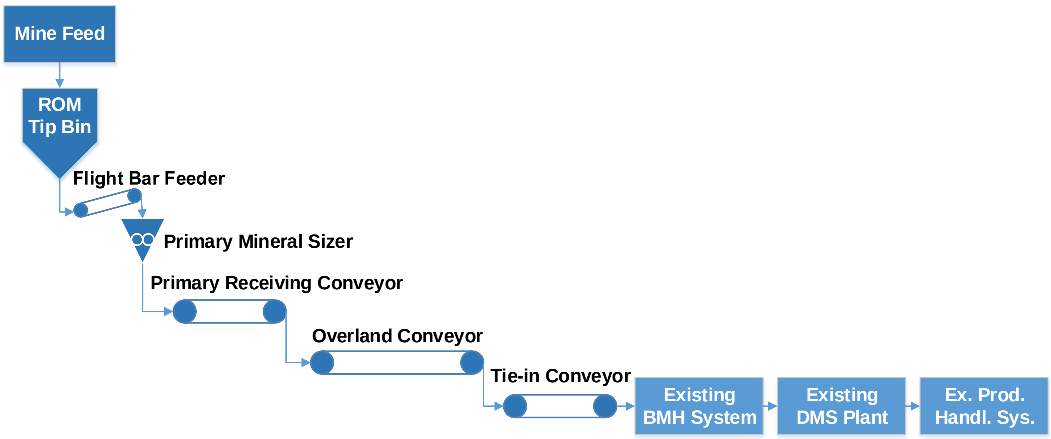


Figure 1.4: System Overview

The mine and the BMH system were designed in such a way that the critical constrained resource (CCR) in the system, the Dense Medium Separation (DMS) Plant, can process an average of 5.8 Million Tonnes Per Annum (Mtpa) (including 5% moisture) from the new coal reserve. A dynamic simulation was required to provide the project review team with the assurance that the materials handling value chain (from mining face to DMS Plant) can deliver 5.8 Mtpa.

1.4 Problem Statement

Giovanni et al. (2017) stated that one of the most significant risks of a mining project is that it does not deliver production in line with the volumes committed in the project investment proposal. This risk was not sufficiently mitigated in the case of Coal Mine A. The mine did not achieve the yearly production targets during the mining of Resource 1 from 2008 to 2013 (Table 1.1). The mine and the BMH system clearly did not deliver the expected amount of coal, such that the DMS Plant could run at design capacity (6 MT). The shortfall had a drastic impact on the mine's revenue.

Table 1.1: Mine A Historical Performance

Year	ROM (MT)	DMS Capacity (MT)	Shortfall (MT)	Shortfall (% DMS Capacity)
2008	4.0	6	2.0	33
2009	5.2	6	0.8	13
2010	5.4	6	1.6	27
2011	5.2	6	1.8	30
2012	4.5	6	1.5	25
2013	4.6	6	1.4	23

Mining companies have been investigating opportunities to reduce production costs through efficiency improvements, maximising equipment availabilities, and better planning (Roberts, 2002). To achieve these objectives, dynamic simulation software is used as an input into the design and planning of both surface and underground operations. During the LOM extension project study phases of Coal Mine A, Modelling and Simulation (M&S) was conducted to mitigate potential poor production performance post the project phase. There was an element of risk associated with the dynamic simulation itself. The approach was new, and there was a need to scrutinise production information, and thoroughly validate the simulation results.

1.5 Significance of Research

There was limited information available about mine performance post project investment. Williams (2004) stated that it is important to learn from the mistakes made on historical projects, such that the same mistakes on current and future projects can be avoided. However, lessons learnt workshops or project post-mortems are rarely conducted. Gypton (2002) evaluated the performance of projects in the mining industry, listing inadequate investigation of critical site-specific conditions and inadequate evaluation and interpretation of site-specific data as technical deficiencies. Anbari et al. (2008) discussed the role of post-project reviews which improve organisational performance and increase competitiveness over the long term. A criterion to determine project success or failure is the evaluation of the project against the technical specifications described in the project documentation. Often in project studies, an optimistic view is taken, and some studies are flawed, as a result. Projects that do not conform to agreed specifications are most likely to fail. It is recommended that post-project reviews be conducted, especially in the case of failed projects which will result in an improvement in project development and execution methodologies in future.

Mills (1985) stated that a post-installation appraisal is an effective management tool. The appraisal entails a periodic review of the actual performance of projects and investment programmes. One of the project review deliverables is a comparison of actual performance against management expectations. The results of the appraisal are useful in improving mine performance and decision making within the organisation. In cases where investments are successful, lessons learnt should be adopted as early as possible on current and new projects. In cases where mine performance is significantly below expectations, it is recommended that plans for enhancing profitability be developed and implemented, and results confirmed by comparing the actual results to those projected in the original economic analysis. The dynamics of process operations are often not considered in process engineering and in the development of operating procedures for new facilities (Bonem, 2013). The dynamics of process operations are important considerations for the development of plant start-up procedures, the design of plant for upset conditions, for example, when the feed rate is higher than the nominal feed rate, and the design of plant for batch processing.

The primary aim of the simulation validation is to identify areas of improvement or bottlenecks that will lead to the development and improvement of the simulation such that it can be used with a high confidence level in future projects. The simulation consists of four components, the:

- Mining Model;
- BMH G2 Simulation Model;
- DMS “Black Box” Model; and
- Product Handling “Black Box” Model.

The lengths of the buffers of the mining activities were determined to ensure that there was no interference between interdependent activities and that planned production can be achieved in practice. This work was conducted using Palisade’s @RISK Monte Carlo simulation software.

Due to time constraints on the project, it was not possible to combine the four models into a single simulation model of the complete system. The mining model is a simplified representation of the production the mine could achieve. The BMH G2 model is a detailed representation of the crushing and conveying system. The DMS Plant and product handling models are also simplified representations. These models were combined (integrated) and the simulation results then analysed. The view from the discipline-specific experts and the project review team are that both the approach and the results are acceptable. It was confirmed telephonically that this specific surface mine materials handling value chain simulation approach is new and has not been used previously by mining conglomerates such as Anglo American Coal, Glencore and Sasol. Therefore, it is essential to conduct a thorough validation of the simulation results.

1.6 Research Aim and Objectives

The aim of the research is to determine whether the specific methods employed for the dynamic simulation should be used on future projects.

The objectives of the research are:

- To discuss the principles and methodologies used in the development of the dynamic simulation;
- To document the actual performance of the mine, BMH systems and DMS Plant, and to compare this against the simulation predictions;
- To validate the dynamic simulation and to draw conclusions about its accuracy and effectiveness; and
- To document lessons learnt and potential shortcomings of the simulation, and to discuss recommendations for improvement.

1.7 Methodology

The methodology used is as follows:

- Conduct research on the topic of M&S at the University of the Witwatersrand Libraries. Conduct searches on internet-based technical information databases, which include EngineeringVillage, ScienceDirect and OneMine. Summarise and document the information applicable to M&S in the mining industry;
- Review the Coal Mine A LOM extension project dynamic simulation and document the work conducted;
- Review and document the work conducted to determine the rules that govern the buffer management of the different mining activities and the required lengths of the buffers;
- Using aerial photography from the mine survey department, determine the buffer lengths of the different mining activities during the validation period and compare this to the mine design requirements;
- Obtain records of downtimes of the coaling equipment during the validation period, calculate the equipment availabilities and

utilisation on coaling activities, and draw comparisons to the simulation;

- Using the availabilities of the coaling equipment and production information, calculate the mine production in Tonnes per Hour (t/h) during the validation period;
- Obtain records of downtimes of the BMH system and DMS Plant during the validation period, calculate the availabilities, and draw comparisons to the simulation; and
- Using historical instrumentation readings, calculate the production (t/h) of the BMH system and DMS Plant during the validation period.

1.8 Structure of the Report

Chapter 1 commences with a description of Coal Mine A and the mining method employed. The Coal Mine A LOM extension project scope is also explained. The motivation for this research and the significance of the topic are provided. Thereafter, the research aim and objectives, and methodology are discussed.

Chapter 1 contains an overview of M&S and commences with a brief history of M&S. The term modelling and the types of models and probability distributions are defined. The definition of simulation, types of simulation, simulation development and analysis, Theory of Constraints (TOC) principles, and simulation software are discussed. The purposes, advantages and disadvantages of M&S are explained. The subjects of verification, validation and credibility are then elaborated on.

Chapter 3 is a description of the dynamic simulation conducted for Coal Mine A. The modelling methodology and rules are detailed. A description of the dynamic simulation and the assumptions made are provided. The inputs and outputs of the simulation are explained. On the mining side, the work conducted to determine the mining activity buffers based on TOC principles is discussed. The available days, the Coaling Operating Time (COT), and the feed rate to the ROM Tip are explained. For the BMH and DMS Plant sub-systems, a description of the available days, Direct Operating Time (DOT), and feed rate inputs have been included. A discussion is provided on the Buffer Silo production (t/h) sensitivity and Raw Coal Stockpile level (t) analysis. The prediction of the achievable annual production by the simulation is then elaborated on. Work conducted on the rail load-out station capacity study is also explained.

Chapter 4 is a discussion of the validation work conducted. In the mining discipline, the actual buffer lengths of the mining activities are analysed and compared to the buffer length requirements, as per the mine design. The COT for the Hitachi EX3600 Excavator and DOT for the Komatsu 730e Trucks are calculated and compared to the simulation. The comparison includes mine production performance. The actual BMH system and DMS Plant availabilities and production performance are also described. An analysis of the complete system (Mining, BMH and DMS Plant) is included, and conclusions are made on the effectiveness of the simulation.

Chapter 5 is the last chapter in which conclusions are made and recommendations are drawn from the research conducted. Recommendations for future work are also provided.

2. MODELLING AND SIMULATION (M&S) – AN OVERVIEW

2.1 Introduction

M&S has grown into a separate discipline, which has its own body of knowledge (Banks & Sokolowski, 2009). Simulation is viewed as a branch of science, as determined by the American Geophysical Union. M&S is the creation of a computerised mathematical model which represents a physical system, and the experimentation with the model itself (Chung, 2004). A detailed literature review on M&S was conducted, which provides the basis of the information in this chapter. A brief history of M&S in the context of mining history, which dates back to 1961, describes the work conducted in the field and provides a sense of how M&S has evolved over time.

The terms modelling and simulation are defined separately. The types of simulation models (deterministic and stochastic), model entities, activity durations and delays, and types of probability distributions are described. The definition of simulation, which is quite broad, includes the value of simulation and the development and analysis of simulations. TOC principles and types of software used in simulations are described. A description of the types of simulations is also provided. The purposes of M&S are explained, followed by a lengthy discussion of the advantages and disadvantages of M&S. The subjects of verification and validation are relevant to this research report. A description of these two subjects and the process to obtain credibility in a model is provided.

2.2 History of Mining Simulations

M&S in the mining industry has a notable history. Computer simulation has increased in popularity since the 1960s, and a large amount of research has been conducted to make simulation reliable and pragmatic (King, 2012). The first mining simulation was conducted by Rist (1961) using Symbolic Programming System Language, according to Sturgul (2016). Using the simulation, Rist (1961) calculated the optimal number of trains required for a haulage level at an underground molybdenum mine. During the 1960s, many mining simulations were built using a computer language called Fortran (Sturgul, 2000). Considering current simulation software capabilities, Fortran was an inefficient way of programming due to the use of punched cards, which made both the writing and debugging of programmes very time-consuming.

Falkie & Mitchell (1963) conducted research at an underground coal mine in Pennsylvania, United States of America (USA) on a rail haulage system. This work contributed to the use of Monte Carlo simulation methods in stochastic simulation models. Sanford (1965) was the first to simulate a belt conveying system in Fortran successfully. In 1968, BELTSIM, a large Fortran programme, was developed at the Virginia Polytech Institute and State University in the USA. Morgan & Peterson (1968) developed a stochastic simulation of a surface mining operation. Suboleski & Lucas (1969) presented research on a Fortran programme called SIMULATOR1, which was designed to simulate the bord and pillar mining method. Bauer & Calder (1972) explained the advantages of using the General Purpose Simulation System (GPSS) to simulate the load-haul-dump mining activity for open pit mines. GPSS was used by Steiker (1982) to simulate the rail haulage system of an underground mine. Wilson (1984) described the use of GPSS to simulate the rail transport of ore from platinum mines in Africa. Hancock & Lyons (1984) described a computer simulation package known as SIMBELT4, which was used to calculate the production (t/h) at specified points in a belt conveying system, and to approximate the tonnage of ore in each storage bunker.

Combining the mining and beneficiation plant details in one integrated simulation model significantly improves the robustness of the final design. A BMH G2 simulation was completed at Sasol's Twistdraai Coal Mine (Turner, 1999). The process at Twistdraai is similar to the process intended to be validated in this research report (Figure 2.1). In the engineering phases of the project, the simulation was key to the optimisation of the coal transport, stacking, blending and beneficiation plant designs. The simulation was also used as an input into the control philosophy and maintenance strategy of the mine. The simulation was invaluable to the project development process and resolved many issues, including the:

- Integration of the mining (six-day work week) and beneficiation plant (seven-day work week) operational calendars; and
- Interface between the dispatch requirements of the train load-out system and the beneficiation plant.

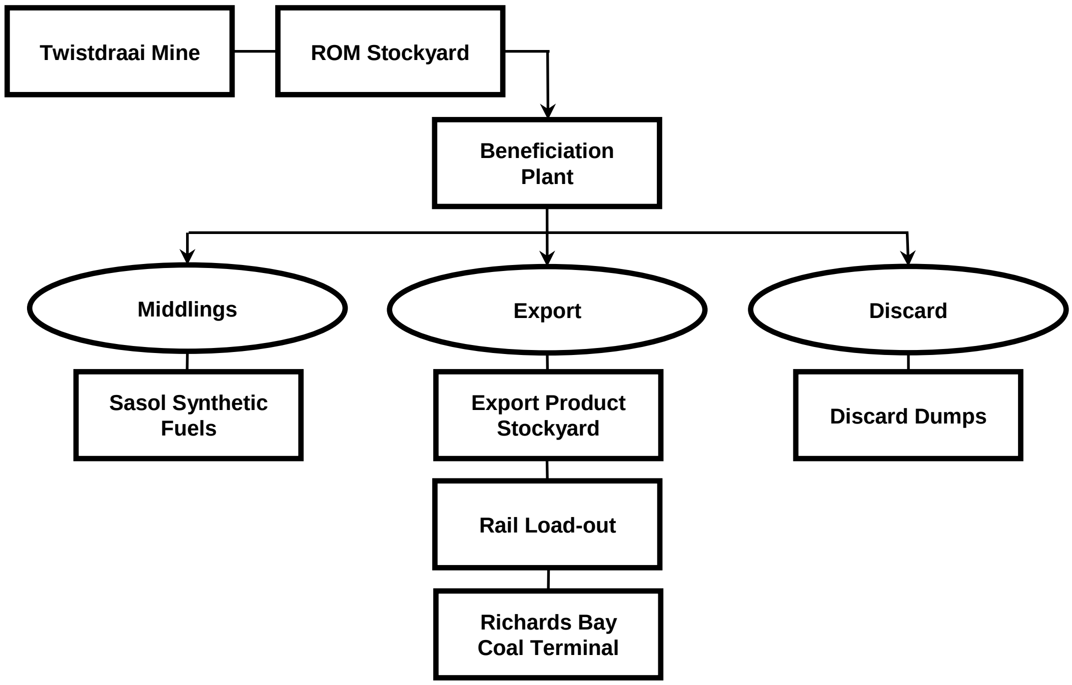


Figure 2.1: Twistdraai Project Processes (Turner, 1999)

Hoare (2007) stated that the interaction between sub-processes of a system is likely to negate the impact of improvements made to individual system components in isolation. The need for an integrated system approach (Figure 2.2) had thus been stressed. The capacity of a process or system is limited by the sub-system, which is identified as the bottleneck. The key to maximising production is the understanding of the impact variability has on component performance, sub-process performance and, most importantly, the total integrated system performance.

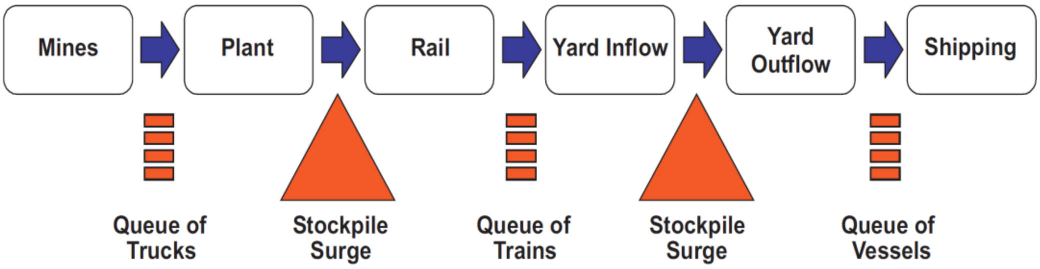


Figure 2.2: Total Integrated System Approach of an Export Supply Chain (Hoare, 2007)

Herbst et al. (2012) stated that the mineral processing industry requires accurate production simulators for the design of future plants and expansions. Simulations are recommended to include the impact of discrete stochastic events, such as scheduled and unscheduled maintenance, making it possible to analyse the relationships between availability, equipment sizes, and plant capacity. A further recommendation is that plant interlocks be included in the simulation. This approach was tested in MetroProSim (Figure 2.3) and was also successfully validated using plant operational data.

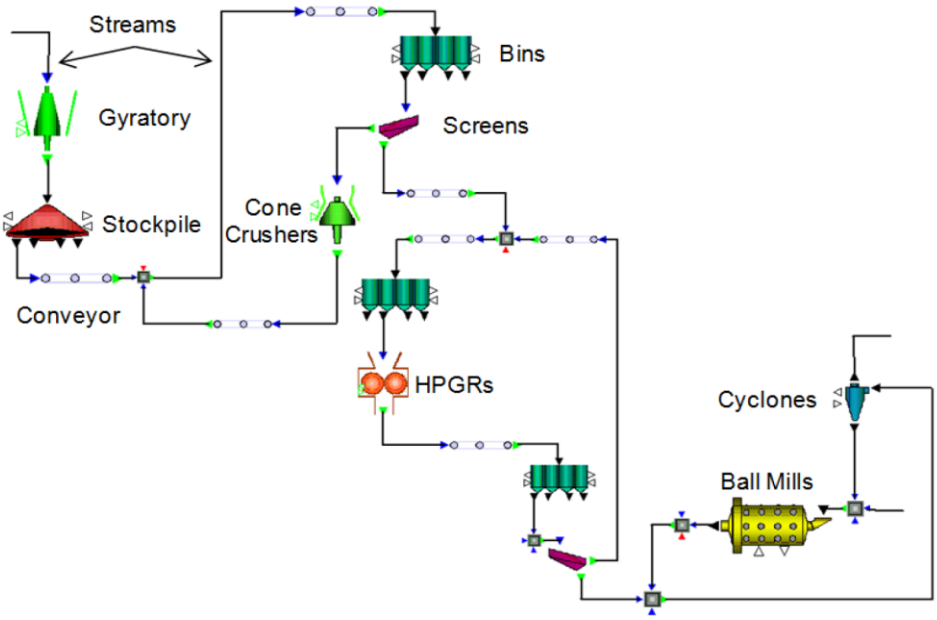


Figure 2.3: MetroProSim Plant Flowsheet (Typical) (Herbst et al., 2012)

Camargo et al. (2018) proposed a Method of Integrated Process Simulation (MIPS) which can be used to motivate the approval of capital projects in the mining industry. Research work concluded that optimisation models are generally not representative of the full production chain and cover specific processes only. A model of the production chain of an iron ore operation was developed, and the modelling method considered the dynamic, stochastic and systemic characteristics of the operation. Model input variables included material qualities, material volumes, operational parameters and operational costs. Scenarios were then developed, and model runs were conducted for each scenario. The production (t/h), operational costs, and product qualities were calculated for each of the scenarios. The model outputs enabled the calculation and comparison of various financial metrics. Limitations of the model include difficulty in proving the viability of the method due to its complexity, high resource requirements for model development, and high iron ore material variability, which require periodic updates of the models' estimating functions and probability distributions.

2.3 Modelling

2.3.1 Definition of Modelling

A model is designed to show the anatomy of the system and is a means of approximating a real-world event (Czaplicki, 2009). A system is defined as an assembly of components which interact with one another to achieve a defined set of objectives (Law, 2007). Operational data is required during model development. Following model development, the calibration of the model may be required. As confirmed by Banks et al. (2010), it is only necessary to consider the aspects of a system which are related to the problem to be investigated. The development of a model is followed by simulation.

2.3.2 Model Entities, Activity Durations and Delays

An entity is an object that can be explicitly defined (Banks, 1998). An entity can be static or dynamic, and it may have unique or common attributes when compared to other entities. The start and end of an activity should be defined before running a model. An activity duration can be a static input into a model, a random value from a probability distribution, an input from a file, or a result from an equation. A delay is defined as a type of event caused by a system condition which has an indefinite duration.

2.4 Types of Simulation Models

There are two types of simulation models which are called deterministic and stochastic models.

2.4.1 Deterministic

A deterministic simulation model is defined as a model which does not contain any random or probabilistic components (Law, 2007). In deterministic models, the system component relationships need to be defined and the input values specified before the output can be determined.

2.4.2 Stochastic

A stochastic simulation model is a type of model which has random input components (Law, 2007). The outputs of stochastic models are random estimates of a system's behaviour.

2.5 Types of Probability Distribution Functions

The following is a description based on Chung (2004) of the Probability Distribution Functions (PDFs) relevant to this research report.

2.5.1 Triangular Distributions

The triangular distribution (Figure 2.4) is applied to data that is not uniformly distributed. There are three parameters in this type of distribution: the maximum value, minimum value, and most common value. It is not necessary for the most common value to fall equally between the minimum and maximum value and the distribution itself does not have to be symmetric. The mean and variance of the triangular distribution are shown in Equation 2.1 and Equation 2.2 (Chung, 2004).

$$\boldsymbol{mean = \frac{a+m+b}{3}} \tag{2.1}$$

where: a = minimum value

m = most common value (the mode)

b = maximum value

$$\boldsymbol{Variance = \frac{(a^2+m^2+b^2-ma-ab-mb)}{18}} \tag{2.2}$$

where: a = minimum value

m = most common value (the mode)

b = maximum value

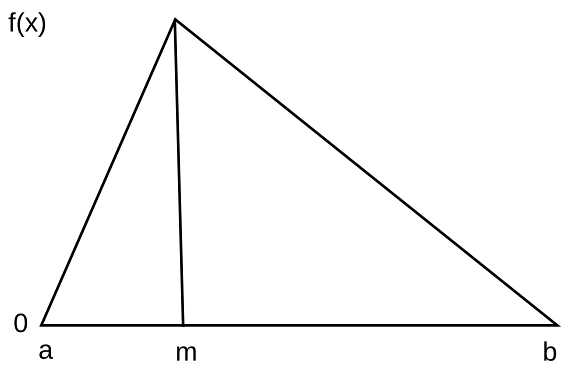


Figure 2.4: Triangular Distribution (Chung, 2004)

2.5.2 Normal Distribution

A normal distribution (Figure 2.5) has an equal number of values greater than or less than the mean and it is symmetrical. The normal distribution has two parameters, which are the mean and the standard deviation. Equation 2.3 represents the normal distribution probability function (Chung, 2004).

$$\boldsymbol{f(x)} = \frac{\mathbf{1}}{\boldsymbol{\sigma\sqrt{2\pi}}}\boldsymbol{e}^{-(x-\mu^2/2\sigma^2)} \qquad (2.3)$$

where: μ = mean value

σ = standard deviation

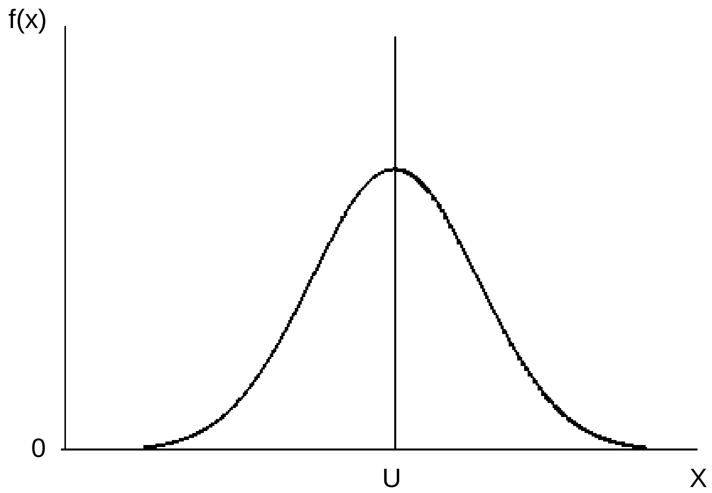


Figure 2.5: Normal Distribution (Chung, 2004)

2.5.3 Weibull Distribution

A Weibull distribution (Figure 2.6) is the most widely used distribution for modelling the life of a machine (Winston, 1996). It is used for distributions that do not have values less than zero. Most symmetric distributions have this characteristic, such as normal distributions that represent process times. The Weibull distribution has two parameters: the α shape parameter and the β scale parameter. If β < 1, the machine's lifetime has a decreasing failure rate property. This means that the longer the machine operates, the less likely it is to fail during the next few seconds. If β > 1, the machine's lifetime has an increasing failure rate property (Chung, 2004). This means that the longer the machine has operated, the more likely it is to fail during the next few seconds. If β = 1, then the machine's lifetime is exponential and has a constant failure rate property or lack of memory (Chung, 2004). The lack of memory property implies that no matter how long a machine has been operating, its chances of failing during the next few seconds remain the same. The shape of the Weibull distribution, which is dependent on the shape and scale parameters, can range from that of the exponential function to the normal distribution function. Equation 2.4 describes the probability function of the Weibull distribution (Chung, 2004).

$$\boldsymbol{f(x) = \propto \alpha\beta^{-\alpha}x^{\alpha-1}e^{-\left(\frac{x}{\beta}\right)^{\alpha}}, for\ x > 0, 0\ otherwise} \tag{2.4}$$

where: α = shape parameter

β = scale parameter

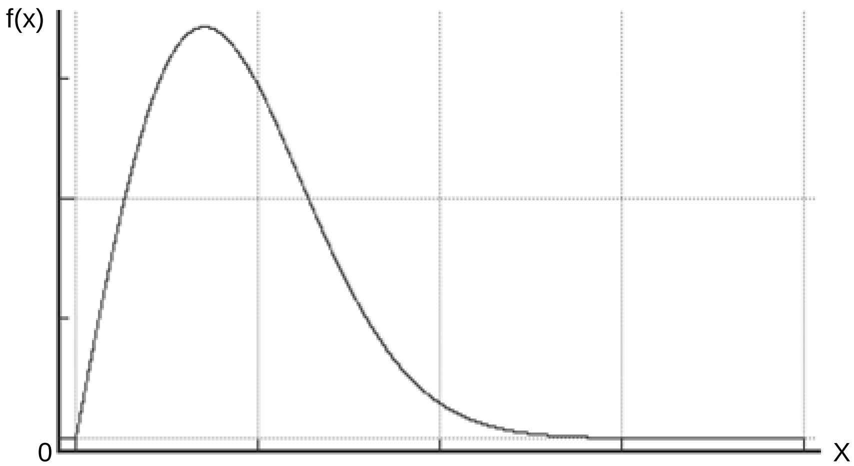


Figure 2.6: Weibull Distribution (Chung, 2004)

2.5.4 Beta Distribution

The beta distribution (Figure 2.7) only covers a range between 0 and 1. If required, the distribution can be offset or scaled with a multiplier value. This type of distribution, like the Weibull distribution, has two parameters: the α shape parameter and the β scale parameter. The formula for the probability distribution of the beta distribution is described in Equation 2.5 (Chung, 2004).

$$\boldsymbol{f(x)} = \frac{\Gamma(\propto +\boldsymbol{\beta})}{\Gamma(\boldsymbol{\alpha})\Gamma(\boldsymbol{\beta})}\boldsymbol{x^{\alpha-1}(1-x)^{\beta-1}, for\ 0 < x < 1, 0\ otherwise} \qquad (2.5)$$

where: α = shape parameter

β = scale parameter

r = Weibull and gamma distributions

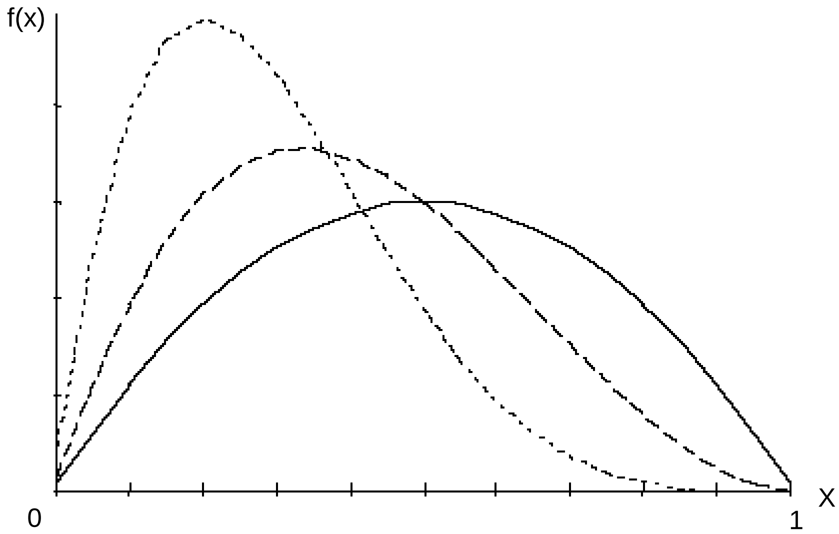


Figure 2.7: Beta Distribution (Chung, 2004)

2.5.5 Programme Evaluation and Review Technique (PERT) Distribution

According to Vose (2008), the PERT distribution (Figure 2.8) is based on the beta distribution. The PERT distribution uses the same parameters as the triangular distribution, which are the minimum (a), most likely (b), and maximum (c) parameters. Equation 2.6 describes the formula of the probability distribution of the PERT distribution (Chung, 2004).

$$\boldsymbol{PERT(a, b, c)} = \boldsymbol{Beta}(\propto_{\mathbf{1},} \propto_{\mathbf{2},}) \times (\boldsymbol{c} - \boldsymbol{a}) \times \boldsymbol{a} \qquad (2.6)$$

where:

$$\propto_1 = \frac{(\mu - a) \times (2b - a - c)}{(b - \mu) \times (c - a)}$$

$$\propto_2 = \frac{\propto_1 \times (c - \mu)}{(\mu - a)}$$

$$Mean(\mu) = \frac{a + 4b + c}{6}$$

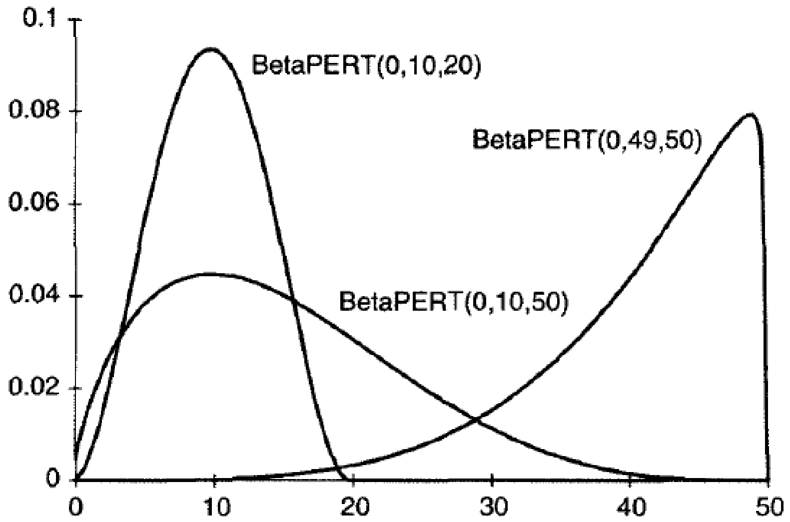


Figure 2.8: Examples of PERT Distributions (Vose, 2008)

2.6 Simulation

2.6.1 Definition of Simulation

Many definitions of the word "simulation” exist. Banks (1998) and Hoare (2007) stated that simulation is the technique of building a computer model that imitates the behaviour of a system or process to conduct a scientific study of the system. Simulations provide insight into how a system will operate under a given set of parameters, but they do not solve problems (Sturgul, 2016). The simulation of complex systems requires a detailed understanding of each system component. An analysis can then be completed on the system under specific conditions and certain assumptions, which can be used as an input into a design optimisation exercise. A simulation enables the analysis of periods of low system performance and the impact of potential system improvements. Banks et al. (2010) stated that simulation can generate an artificial history of a system which can be used to draw conclusions on the operational characteristics of the system. Traditional simulation is used for analysing systems such that operational or resource policy decisions can be made.

2.6.2 The Value of Simulation

Simulations can provide invaluable insight into a system, but only if used correctly. McKee & Wiseman (1991) stated that the contribution of simulation at project feasibility study level depends greatly on the predictive capability of the models. Simulation has become a standard requirement for project feasibility studies at most mining companies. Liu & Spencer (2004) echo this sentiment, stating that dynamic simulation is a great tool which can be used to gain an understanding of a system and system performance with minimum cost. This view is shared by Dindarloo and Siami-Irdemoosa (2016), who state that simulation can be used to study a system’s dynamics and to conduct sensitivity analyses on different alternatives.

A simulation can be used to analyse existing systems and the impact of potential upgrades to the system, and to predict the performance of new systems based on certain assumptions (Banks, et al., 2010). Simulation is an indispensable problem-solving methodology for the solution of many real-world problems (Banks, 1998). According to Lynch & Morrison (1999), the success of simulation necessitates the formation of a reservoir of professional skills for well-known commercial software simulation packages. Simulation has grown to the extent that several organisations have been formed whose principal business is to use simulation and to carry out training, software development and technology transfer.

2.6.3 Simulation Development

There are two sides to developing a dynamic simulation (Askew, 2009). The first is the technical coding of the simulation using a computer package by an experienced developer. The second is the development process of the simulation, which requires interaction between the simulation developer and stakeholders. The development process requires a skill set that enables the developer to gather, verify and validate information from the stakeholders. The presentation of the simulation to the stakeholders enables them to understand the simulation and make decisions when required. This is of greater value than the output of the simulation. The simulation developer must be competent in the use of the simulation software, knowledgeable of the domain being simulated, and have the communication skills to gather and resolve conflicts during the development of the simulation.

2.6.4 Simulation Analysis

Simulation analysis is an investigation of a system's behaviour after a simulation is run one or more times (Banks & Sokolowski, 2009). As part of the analysis process, verification and validation are completed and findings, recommendations and conclusions are noted.

2.6.5 Theory of Constraints Principles

The mine plan of Coal Mine A was based on TOC principles (Figure 2.9). The processes contain two basic phenomena, namely, statistical fluctuation and interdependent events. Goldratt (2004) lists three areas of importance for improvements: production, inventory and operating expenses. The TOC is aimed at achieving continuous improvement in a process of five steps (Figure 2.9). The TOC states that the bottleneck would determine the capacity of the production line and that all other processes should be subordinated to the bottleneck. The adoption of TOC principles into a mine plan may provide assurance that planned production can be achieved in practice.

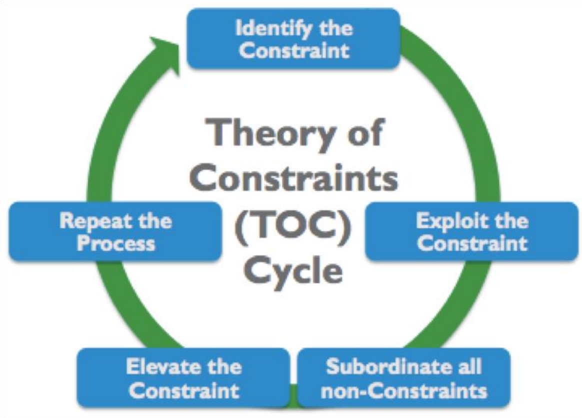


Figure 2.9: Steps in TOC Cycle (Lean & Six Sigma University, 2018)

The required buffer lengths for each of the different mining activities were calculated, including the required in-pit inventory. Figure 2.10 shows the buffer lengths (a to i) of sequential mining activities of a typical surface (terrace) coal mining operation.

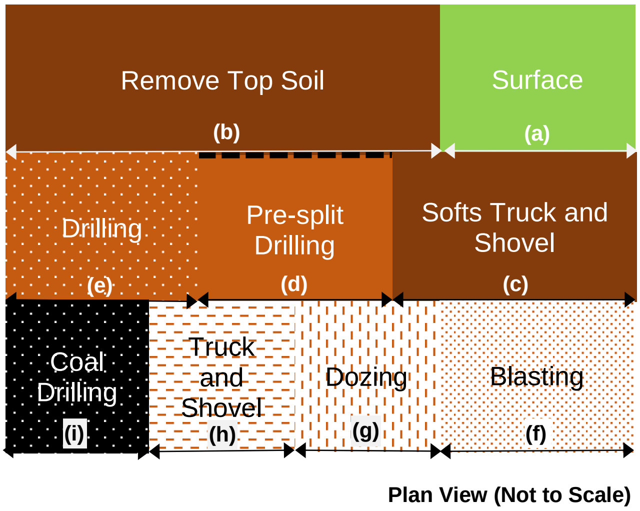


Figure 2.10: Mining Activity (Top Soil Removal to Coal Drilling) Buffers of a Typical Surface (Terrace) Coal Mining Operation

An investigation into the identification of the CCR of a Sasol mine was conducted by Van Heerden (2017), who made use of TOC principles developed by Goldratt (2004).

2.7 Types of Simulations

The following is a summary of the types of simulations from the works of Banks (1998), Law (2007), Banks & Sokolowski (2009), Banks et al. (2010), and Sturgul (2016).

2.7.1 Discrete Event Simulation

A discrete event simulation is dynamic in nature and time-dependent. In discrete systems, a finite number of events can take place at any given point in time. An event is defined as an immediate occurrence which causes the state of a system to change. The state of a system refers to a group of variables which can describe the system to a sufficient level of detail at any point in time. This group of variables, called state variables, changes instantaneously at separate points (events) in time. A clock is used in discrete event simulation to record time and to trigger events. Time can be compressed or expanded to facilitate analysis requirements. A truck and shovel (cyclic queue) system is a good example of a discrete event simulation. The GPSS computer programming language can be used for this type of simulation.

2.7.2 Continuous Simulation

In continuous simulations, state variables change continuously with respect to time. State variables are used to define the system parameters.

2.7.3 Static Simulation

Static simulations, also known as Monte Carlo simulations, are representations of systems that are time-dependent or independent of time.

2.7.4 Dynamic Simulation

A dynamic simulation model represents a system as it changes and develops over time.

2.7.5 Deterministic Simulation

A deterministic simulation has a known set of inputs and contains no random variables. The outputs generated by the simulation are unique.

2.7.6 Stochastic Simulation

A stochastic simulation has one or more random variables as inputs. Because of the random inputs, the model outputs are also random and can only be considered estimates.

2.8 Simulation Software

2.8.1 Gensym G2

Gensym's G2 can be applied to any industry and used to simulate any system or process (Gensym, 2018). G2 has the capability to transform real-time operations data into an automated decision-making tool. A graphical programming language called G2GL has been incorporated into G2's operating platform which is based on the Business Process Execution

Language for Web Services standard. The use of G2 allows teams to work more productively and increases the chances of project success.

2.8.2 Palisade's @RISK software

Palisade's @RISK software is a type of risk and decision analysis software (Palisade, 2018). It is part of the DecisionTools Suite developed by Palisade, and it is a Microsoft (MS) Excel add-in that makes it easier to perform spreadsheet simulations (Winston, 1996). Risk analysis is performed using Monte Carlo simulation, which mathematically and objectively analyses many different scenarios and illustrates the probabilities and risks associated with each one.

The name "Monte Carlo" simulation originated during World War II when this type of simulation was used to resolve problems related to the development of atomic bombs. A Monte Carlo simulation is defined as a stochastic, discrete event simulation. Monte Carlo simulations utilise random numbers to solve problems that are stochastic in nature (Law, 2007). Palisade's @RISK software can run several model iterations and, with each iteration, it can input a different value into a desired cell.

2.8.3 Spreadsheet Simulation

Discrete-event and Monte Carlo simulations can be conducted using a Spreadsheet simulation in MS Excel. Spreadsheet simulations are set up to solve problems which are not complex in nature (Law, 2007). The random number generator in MS Excel can generate random values from basic probability distributions, for example, normal, uniform, binomial and Poisson. Spreadsheets, however, have the following limitations:

- Complex data structures are not available;
- Complex algorithms are difficult to implement;
- Simulation execution time is considerably longer compared to some other available simulation packages; and
- Data storage space is limited.

2.9 Purposes of M&S

The purposes of M&S, as explained by Chung (2004) and Banks et al. (2010), are listed below.

- Simulation allows one to gain insight into the operation of both simple and complex systems and to understand the interactions between the different processes of a system. Simulation makes it possible to study an existing system without having to conduct any physical trials on the system itself. Some systems are so critical to the operation that it is not possible to make any temporary operational changes for system analysis purposes;
- With simulation, it is possible to improve system performance. This could be through the development or change of operating, resource and environmental policies;
- Proposed systems can be simulated, and performance characteristics understood prior to implementation. Different capacities of equipment can also be simulated. The cost of modelling a new system is minimal compared to the capital required for a new manufacturing process; and
- Information required for decision making can be generated via simulations, such that informed decisions can be made on whether to implement a project.

2.10 Advantages of M&S

The following advantages of M&S have been identified through a review of research conducted by Winston (1996), Banks (1998), Chung (2004), Law (2007), Banks & Sokolowski (2009), Banks et al. (2010), Brooks (2013), and Sturgul (2016):

- Simulations work both swiftly and accurately and can solve many problems in many different types of systems;
- Systems and the operation thereof can be better understood;

- M&S allows “goal seeking” to be conducted in which system changes can be confirmed to achieve a desired target;
- Computer simulation allows for experimentation in a compressed or expanded amount of time such that thorough analyses can be conducted. Simulation also allows multiple runs or replications to be conducted such that the confidence level of the results can be increased;
- Investigations into new control philosophies, maintenance strategies, and company operating procedures can be conducted without interrupting the actual system(s). Simulation can be used to identify areas of poor plant performance without the inconvenience of having to conduct trials on the plant itself;
- Problems in complex systems and system constraints can be identified, and the impact of solutions to improve production can be investigated;
- Simulations can be easily demonstrated and presented via dynamic animations. Animations illustrate the workings of the model and describe the interrelationships between the different processes. Animation allows for the visualisation of the current operation and potential solutions to problems. The simulation logic and accuracy of the results of the simulation can also be confirmed with animation. Visualisation assists with the understanding and interpretation of the outputs from the simulation. Animation can be used for debugging the model as well;
- M&S allows for the simulation of various “what if” scenarios to aid in decision making;
- M&S provides invaluable input for project investment decisions;
- Simulation contributes to safer designs and improved system operability. It is envisaged that dynamic simulations will become a standard tool for plant design and will be used to troubleshoot operability issues experienced on existing systems;

- With simulation, complex systems that were previously impossible to analyse in detail can now be studied;
- Various software packages have been developed, considerably reducing the time it takes to develop a simulation, Simulation makes it possible to conduct dynamic studies of systems in real time;
- Simulation is sometimes the only type of investigation possible for complex systems with stochastic elements. These types of systems cannot be modelled using analytical methods;
- The performance of existing systems can be estimated under different sets of operating conditions;
- Simulation allows for an options analysis to be conducted in which different system designs can be compared and the best option selected;
- The validity of various hypotheses can be tested via simulation;
- Simulation provides insight into the impact different variables have on system performance as well as the relationships between the variables;
- System bottleneck analyses can be conducted as part of the simulation which allows system constraints to be identified;
- Sensitivity analyses can be conducted using simulation, which could be used to determine how sensitive a system is to changes in operating conditions. A simulation model also allows the user to determine an optimal operating policy;
- Simulation is a key consideration when it comes to investment decisions, and it is a very cost-effective mechanism. The cost of a simulation study is approximately 1% of the total project implementation cost;
- Simulation can be used to determine and confirm the required capacities of different components in a system to achieve a common design goal;

- Simulation can provide further insight into a system, conduct statistical analyses, and validate its design performance. Simulation can predict potential outcomes of system design options and conduct "what if" analyses; and
- Simulations can be performed on both desktop and high-performance parallel computers.

2.11 Disadvantages of M&S

The following disadvantages were identified through the review of research conducted by Banks (1998), Chung (2004), Law (2007), Banks et al. (2010), Bonem (2013), and Brooks (2013):

- Special training is required to build and run simulations. Simulation building is a skill acquired over time. However, simulation software vendors have been developing software which is currently much more user-friendly than previous versions;
- The interrelationships between components of simulations of complex systems may be difficult to confirm, especially when the outputs are random variables because of random inputs. Currently, simulation software packages have output-analysis capabilities which may assist in understanding system component interrelationships;
- Simulation modelling can be onerous and time-consuming;
- Simulation could be erroneously applied to a system which is more suited to the application of an analytical method. Analytical models are not suitable for the analysis of complex systems;
- The use of slower, desktop computers could lead to less than real-time execution of the simulation. Dynamic simulation usually requires computing power beyond the average user and as the simulation becomes more complex, more powerful hardware is required to run the simulation. Advanced hardware can reduce the computational time of a simulation. However, the view is that

the cost of the hardware required is relatively small in comparison to the potential benefits of using a dynamic simulation. Slow simulations are attributed to inexperienced engineers who have simulated too much detail, which is normally not required to achieve desired outcomes. Scoping of the simulation and the definition of battery limits are thus extremely important. Simulation can now be performed faster because of technological advances in hardware and software;

- Most dynamic simulations have been completed with highly complicated and sophisticated mathematics. Due to model complexity, dynamic models are not often constructed. The output of complicated solutions leads to the use of intuition and gut feel to finalise the problem solution;
- Simulation results are based on inputs, and if the input data is inaccurate, the results will be inaccurate as well;
- The simulation of a complex system normally yields a result which is complex in nature, requiring more time and effort to understand;
- Simulations need to be piloted and are not capable of solving problems without intervention. Simulation provides potential solutions to solve the problem;
- Simulation building can be a mammoth task, especially when it comes to the study of large-scale, complex systems;
- There is a tendency to place greater confidence in simulation results than is justified. This is due to the large volume of data produced by the simulation study and the generation of realistic animations. If a model has certain flaws and is not representative of the system, the model results will be inaccurate, no matter how impressive they appear; and
- Stochastic type models produce estimated outputs per set of inputs. Multiple runs per set of inputs are required such that the variability in the model can be understood and results confirmed.

2.12 Verification

2.12.1 Definition of Verification

Banks & Sokolowski (2009) state that verification is an important aspect of any simulation process and an essential prerequisite to the credible and reliable use of a model and its results. Verification is defined as the process of reviewing a model and determining whether the model will satisfy the scope and requirements of the project. A review by the developer and a third party is recommended. The logic in the model and the model inputs and outputs should be confirmed to be correct. If the model is animated, the animation should be compared with the actual system. Debugging should also be used to identify and correct errors in the model during the verification process. When it comes to a large-scale simulation programming, debugging is an arduous task due to the sizeable number of system component groups.

2.12.2 Verification Methods

According to Banks (1998), verification is the process of conducting a detailed review of the simulation programme to ensure that the model precisely represents the system. The following is a description of ways to perform verification:

- Follow the principles of structured programming. The first principle is a top-down design in which a detailed plan of the simulation is developed before the coding activity commences. The second principle is programme modularity, which refers to the development of a comprehensive flowchart which describes the sequence of the various activities, the coding of the model in a structured and logical manner, and the creation of sub-models;
- Document the model development process. This could involve the use of comments during the coding of the model;

- Conduct a review of the model coding, input data, and output data. It is recommended that the review be conducted by specialists in the field;
- Use an Interactive Run Controller (IRC), which is a type of programme debugger that can confirm if the programme functions as intended; and
- Use animation to confirm the programme logic in the model.

2.13 Validation

Validation is an important aspect of any simulation project (Banks & Sokolowski, 2009). According to Law (2007), validation is a means of confirming that a model is representative of a system and that the objectives of the simulation have been met. During validation, the level of confidence in the simulation, the accuracy of the model results, and the range of inputs which would provide credible and useful results are confirmed. If a simulation is valid, it can be used as a decision-making tool for the operation going forward, for both existing and new systems (Banks et al., 2010). If a simulation is not valid, it is not credible and further work must be conducted to establish credibility (refer Section 2.14).

2.13.1 Validation Methods

There are two steps in simulation validation. The steps (described below) are face validation and statistical validation.

- Face validation. Face validation entails a review (by experts) of the simulation and results of the simulation, and the potential update of the model based on the outcome of the review (Banks, 1998). The model should be confirmed to be a true reflection of the system to be investigated. Face validation should be conducted at the end of the model development period before statistical validation commences; and
- Statistical validation. In statistical validation, the output data of the model is compared to data from the actual system. If there

are no significant differences, the model is regarded as valid. If there are significant differences, additional work is required before further analysis. Law (2007) refers to statistical validation as results validation.

2.13.2 Validation Data Collection

Validation data collection is a process that involves the acquisition of data from both the actual system and the simulation model such that both sets of data can be compared.

2.14 Credibility of a Simulation Model

Law (2007) states that a simulation model and its results are credible if the results have been accepted by the key stakeholders. The timing and relationships of validation, verification and establishing credibility are shown in Figure 2.11. The blocks represent the different phases of the simulation study. The actions required to progress from one phase to the next are shown at the bottom of the diagram. The curved arrows illustrate where verification, validation and the establishment of credibility mostly occur throughout the different phases of model development.

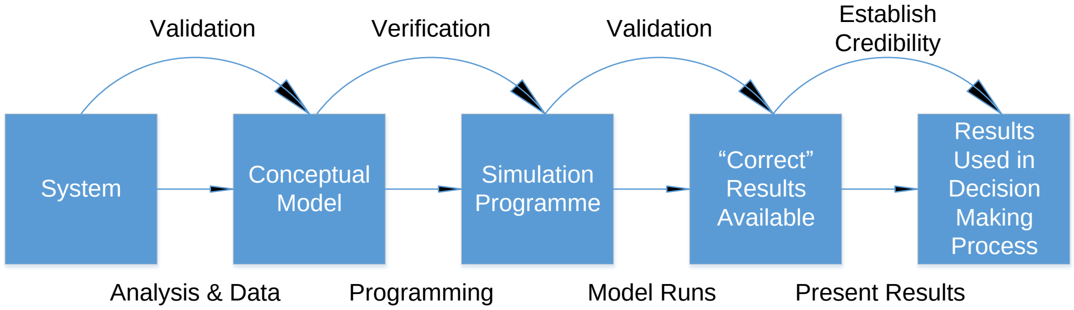


Figure 2.11: Timing and relationships of validation, verification and establishing credibility (Law, 2007)

2.15 Validation Case Study

A dynamic model of an iron ore pellet plant in Quebec, Canada was developed by Noiseux and Côté (2010). Validation was conducted on the model to confirm that the simulation was a correct representation of the plant. The model achieved a 97% accuracy in comparison to plant production performance. Historical plant operational data over a 20-month period was used for the validation. This period was considered sufficient to represent the plant operation and inherent variability of the plant. The model inputs were adjusted such that it was representative of the system over the period. Planned downtime events were also programmed into the model.

The simulation running time was set at 20 months, and the simulation was run a total of 10 times. The reason for conducting 10 simulation runs was that the model included random inputs, such as unscheduled maintenance events, and it generated variable results for each simulation run. The average values for each run over the 20-month period were compared to actual production figures over the same period, and the difference was found to be 1.2%.

The validation process identified potential refinement opportunities which were used to update the model. The impacts of improving the system through the addition of new equipment were investigated using "what-if" scenario analysis in the simulation. It thus became possible to compare different capital investment scenarios, and the simulation became an important decision-making tool. It was found that a 10% increase in annual production could be achieved through the addition of equipment in areas of the plant where the system was constrained, which were the grinding and agglomeration areas. The synergistic impact of improving one area of the plant as opposed to two areas was also investigated. It was found that an amalgamation of the two projects resulted in a greater production increase than the sum of the two individual projects.

2.16 Chapter Conclusions

M&S has greatly evolved since its advent in the early 1960s when simulation software was not user-friendly. M&S currently has its own body of knowledge and numerous books and technical papers have been written on the subject. Mining company officials are reliant on dynamic simulations to provide the assurance required to approve projects. There is overwhelming evidence in the literature review conducted that M&S is an invaluable, powerful tool which can be used for complex system analysis at minimum cost. Simulation can be used to optimise existing systems without the need to conduct trials on the actual system itself. Simulation can also be used in the design of new systems. The advantages of M&S clearly outweigh the disadvantages, and this is a clear indication that M&S can benefit an organisation.

At Sasol's Twistdraai mine, mining and beneficiation plant model integration resulted in a more robust system design, which highlights the importance of model integration. There are two types of simulation models, namely, deterministic and stochastic models, and there are many probability distributions which can be used to simulate unplanned breakdown events. There are also many types of simulations, which include discrete event, continuous, static, dynamic, deterministic and stochastic simulations. The specific type of simulation must be carefully selected to suit the application or system to be analysed. The use of TOC can be an invaluable input into mine plan development and can ensure that planned production is achieved in practice. There are currently many software simulation packages available on the market, which cater for many user requirements. These software programmes have output-analysis capabilities which reduce user computational requirements.

Verification was described as a critical activity in the simulation development process, and it is imperative that experienced simulation developers are used. The discussion of the simulation with stakeholders is of greater value than the numerical output of the simulation. Validation is an important aspect of any simulation project, and it is a prerequisite for the credibility and reliability of a model and its results. A simulation model and its results have credibility if key stakeholders accept them as correct. Model results should be compared with actual plant performance, and the precision of the model should be known and approved by key stakeholders. The next chapter provides a description of the Coal Mine A LOM extension project dynamic simulation.

3. SIMULATION DESCRIPTION

3.1 Introduction

In this chapter, the Coal Mine A dynamic simulation is described in detail. The methodology used in the development of the simulation is described. The simulation development entailed the mobilisation of an integrated team and the modelling of the system. The consulting company used had a G2 simulation specialist who has conducted similar G2 simulations for other clients. Therefore, the decision was taken to utilise the G2 expert system development environment for the simulation. The rules of the model and the sub-systems, including the buffers, are described herein. A comprehensive description of the simulation, which consisted of four models, is then provided. The M&S of each component in the materials handling value chain and the assumptions used is discussed. Monte Carlo Simulation using Palisade's @Risk Software was done to determine the mining activity buffers to ensure that planned mining production can be achieved in practice. The consulting company possessed the competence to conduct the Palisade's @RISK software simulation, having conducted similar simulations for other clients.

The inputs and outputs of the simulation are summarised in Figure 3.1. The mining inputs include the number of available days, the number of available hours, and the feed rate to the ROM Tip. The BMH system inputs include the available hours and the system capacity from the mechanical design basis. The hours available to the DMS Plant and the nominal and peak capacities based on the capacity analysis are also simulation inputs. The simulation outputs include a production sensitivity analysis on the exclusion of a Buffer Silo and the inclusion of Buffer Silos of various sizes. The level of the raw coal stockpile was also analysed with or without a 3 000 t Buffer Silo.

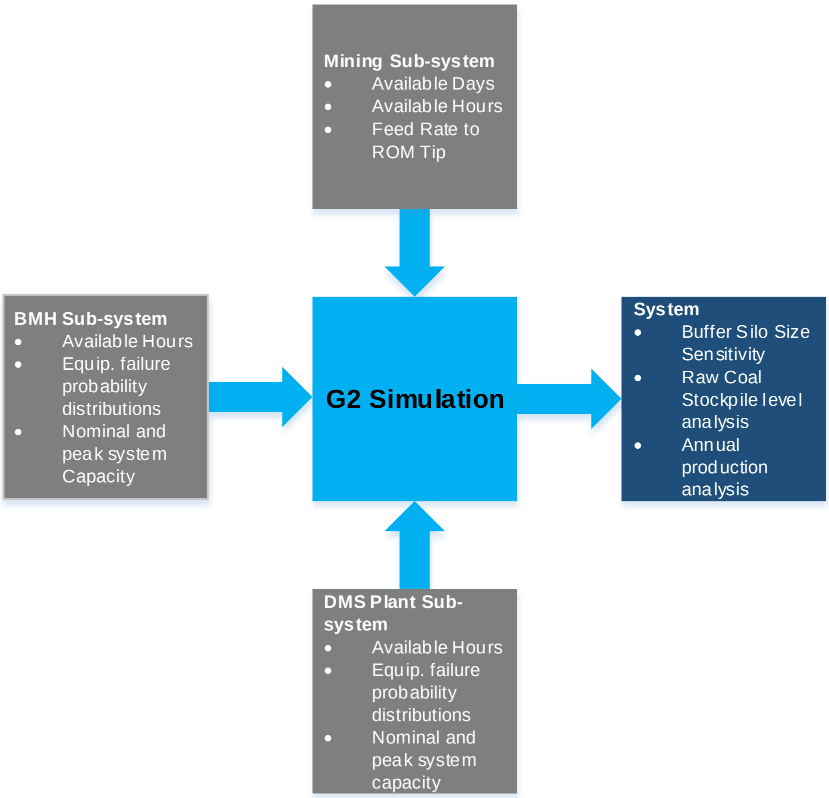


Figure 3.1: G2 Simulation Inputs and Outputs

The ability of the mine to meet the annual production targets is a key consideration. This chapter ends with a description of the rail load-out station capacity analysis.

3.2 Modelling Methodology

The first step in the process was to mobilise a team to work on the simulation. The team (Figure 3.2) was an integrated group consisting of a consulting team, a project team, and a review team. The project team was required to consult with the operations team.

Figure 3.2: Integrated Dynamic Simulation Team

A representation of the materials handling value chain (Figure 3.3) was set up in the Gensym G2 expert system development environment. Planned stoppage events (such as scheduled maintenance, mining shift changes, public holidays, and weather delays) were programmed into the individual model components. Unplanned events (such as equipment breakdowns) were programmed using probability distribution functions of time between failure and time to repair. The probability distribution functions, which represent equipment breakdown profiles, were developed using historical data from the existing plant and equipment. The model used probability distribution functions to simulate unplanned delays. Once the model development was completed, the input parameters were fixed. Two scenarios, the 5.769 Mtpa (average) and 6.484 Mtpa (peak) production scenarios, were investigated. The results were reviewed and the trends then rationalised.

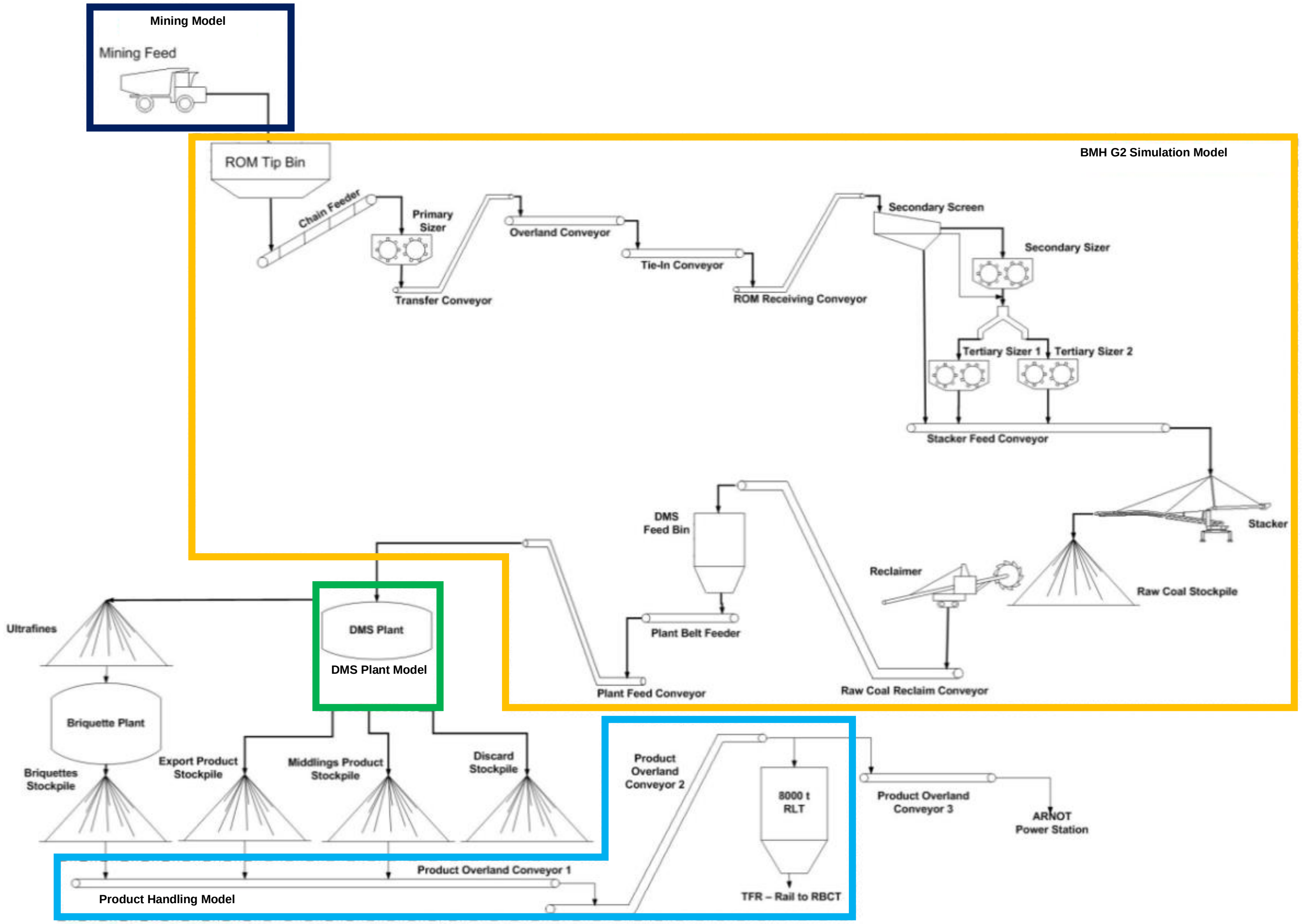


Figure 3.3: System Overview

3.3 Modelling Rules

The materials handling value chain is split into the following sub-systems:

- Mine to Raw Coal Stockpile; and
- Raw Coal Stockpile to DMS Plant.

The buffer between the two sub-systems is the Raw Coal Stockpile. It is, therefore, possible to control each of the sub-systems independently. Whenever a component in a sub-system is stopped, the flow in the whole supply chain is stopped. When the Raw Coal Stockpile is empty, the flow in the sub-system feeding the DMS Plant is stopped. Similarly, the flow is stopped in the sub-system feeding the Raw Coal Stockpile when the Raw Coal Stockpile becomes full. In practice, the raw-coal stockpile should be kept as full as possible so that the DMS Plant or CCR can be run at full capacity. The upfront system should be robust enough to avoid situations where the Raw Coal Stockpile becomes empty.

3.4 Simulation Description

The simulation (Figure 3.3) consists of four models namely:

1. The Mining Model;
2. BMH G2 Simulation Model;
3. DMS Plant “Black Box” Model; and
4. The Product Handling “Black Box” Model.

Due to time constraints on the project, it was not possible to develop a single simulation model of the complete system. The approach to the Gensym G2 dynamic simulation conducted for the Coal Mine A LOM extension project was new and not used at other mines in South Africa. The mining model is a simplified representation of the production the mine can achieve. The BMH G2 model is a detailed representation of the crushing and conveying system. The simulation cost was very minimal (less than 1%) in comparison to the capital investment required for the project.

In the Mine to Raw Coal Stockpile sub-system, the ROM Tip Bin (450 tonnes (t) capacity) is the first component. This component is programmed to simulate the variable flow of material from the mine using an input file generated in Palisade's @RISK software. The next component is the Flight Bar Feeder. An FLSmidth Abon Flight Bar Feeder (Figure 3.4) was installed at the bottom of the ROM Tip Bin and was designed to transfer material from the ROM Tip Bin to the discharge side (head chute) at a constant volumetric rate (FLSmidth, 2018). The only planned delays specified for the Flight Bar Feeder are preventative maintenance events. Delays, such as public holidays and mining shift changes, filtered through to this component from the mining input file developed in Palisade's @RISK software.

The Primary Mineral Sizer (Figure 3.4) was also manufactured by FLSmidth Abon and modelled in the same way as the Flight Bar Feeder. Mineral Sizers are designed to accept a feed of material through the top of the crushing chamber, to draw it through the rotating shafts (laced with teeth), and to crush or size it to a specified product size (FLSmidth, 2018). Size reduction is a critical component of a BMH system (Lynch, 1977). The Primary Mineral Sizer is used to control the maximum flow rate of the sub-system to the Raw Coal Stockpile.

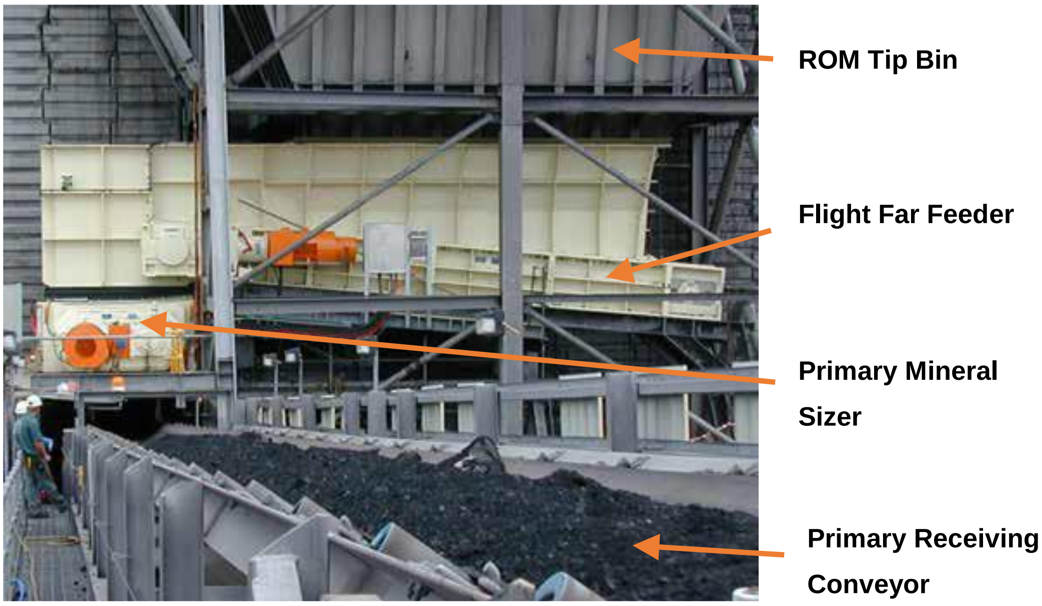


Figure 3.4: FLSmidth Abon Feeder and Primary Mineral Sizer Configuration (FLSmidth, 2018)

The next components in the sub-system are the Primary Receiving Conveyor (Figure 3.4), Overland Conveyor, Tie-in Conveyor, and existing ROM Receiving Conveyor. According to Herbert (2005), belt conveyors (Figure 3.5) are machines used for transporting and elevating material, and they are made up of a belt with a support structure and rollers. The load is transported on the upper surface of the conveyor belt. Conveyors are primarily horizontal-movement, fixed-path, constant-speed material handling systems (Avallone et al. 2007). They may be straight, curved, closed-loop, irreversible, or reversible. The components of a belt conveyor include a head pulley and a tail pulley and idlers which support the conveyor belt. The idlers are supported by a frame or by steel cables. As independent units, belt conveyors are well suited to the rapid transportation of loose material and are used chiefly where large volumes of material are required to be moved along one route. Belt conveyors are used primarily in cases where the load must be lifted steeply or carried across rough country where road construction would be difficult. The conveyor belt itself is an endless flat strip of rubber-covered cotton or rayon fabric, which is laid in plies. Heavily loaded or long belts may be reinforced with steel cable. The type of fabric, number of plies, and any reinforcement present determine the strength of the belt.

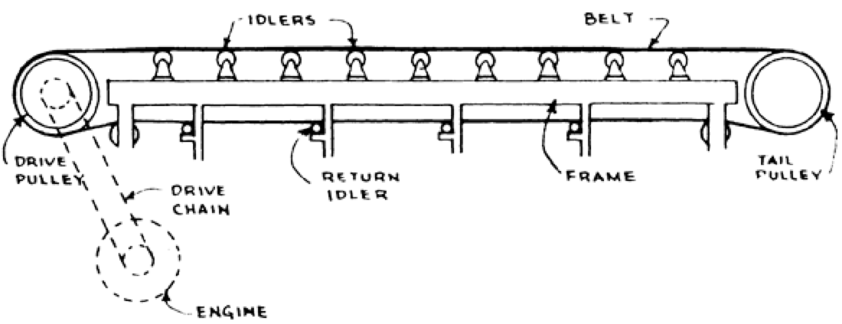


Figure 3.5: Parts of a Simple Conveyor (Herbert, 2005)

The Secondary Screen (Figure 3.6) is the next component in line which has an oversize and an undersize material flow. The screen is a means of separating oversize material from undersize material (King, 2012).

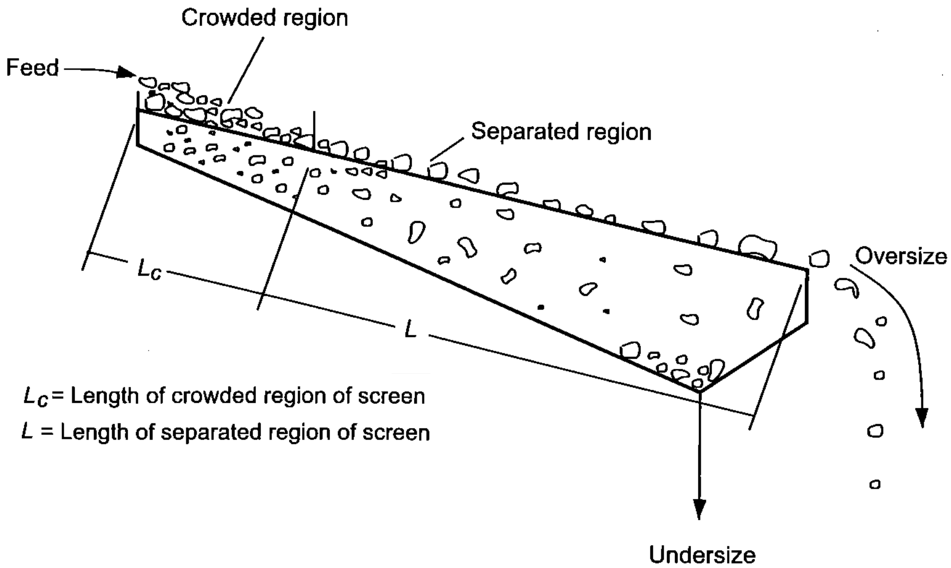


Figure 3.6: Transmission rate (varying) of particles through a wire mesh screen (King, 2012)

The Secondary Screen is modelled as a flow splitter with a specified split percentage and an oversize fraction of 33.3%. The oversize material is crushed by the Secondary Mineral Sizer and Tertiary Mineral Sizers, and then combined with the Secondary Screen undersize material on the Stacker Feed Conveyor. The Stacker Feed Conveyor feeds a Circular Blending System (CBS) and Reclaiming System manufactured by FLSmidth. The CBS is designed for continuous chevron stacking to produce a ring-shaped pile (FLSmidth, 2018). The stacker (Figure 3.7) is mounted on a centre column.

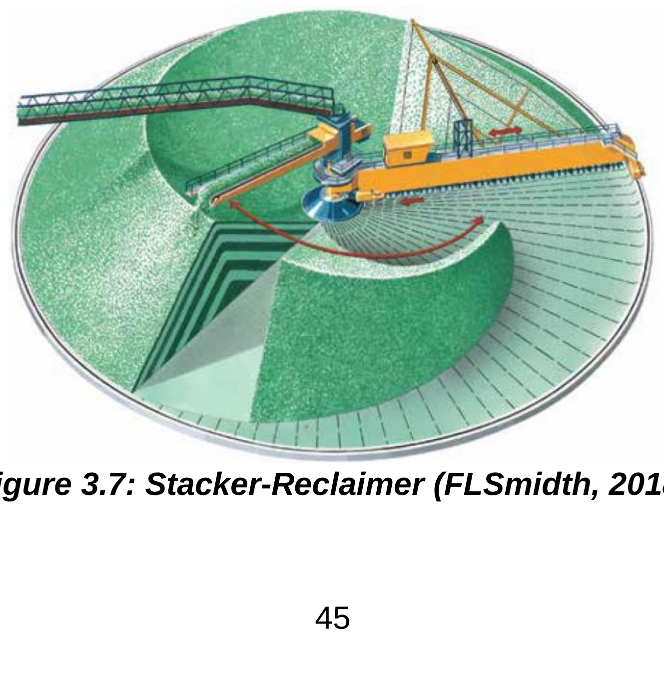


Figure 3.7: Stacker-Reclaimer (FLSmidth, 2018)

Stacking is implemented via a fan-shaped sprinkling action in an arc to ensure appropriate homogenisation of the material. The ring-shaped pile, called the Raw Coal Stockpile, is part of the Raw Coal Stockpile to DMS Plant sub-system. The Raw Coal Stockpile has a total capacity of 60 000 t and a live capacity of 45 000 t. The initial capacity was set at 30 000 t in the model. The stockpile is programmed to be reclaimed completely during the simulation if required. Once empty, reclaiming is programmed to start only when the stockpile level rises above 30 000 t. In practice, reclaiming is implemented via a raking harrow (Figure 3.7), which is part of a bridge type arrangement, shown in yellow. The bridge rotates anti-clockwise around the centre column while the harrow system moves from side to side in a sweeping motion, causing material on the stockpile to slide down to the base of the bridge where a chain system moves the material to a hopper, part of the central column. The homogenised material leaves the stockpile via an underground belt conveyor leading to the DMS Plant Feed Bin. No storage capacity was modelled for the DMS Feed Bin as the bin's 500 t capacity is negligible.

The DMS Plant component was used to model the expected stoppages of the equipment in the plant. DMS is a form of gravity concentration technology involving float-sink separation that is predominantly used in the coal industry (Legault-Seguin et al., 2016). The DMS process relies on the use of a medium (ferromagnetic powder called magnetite) of specific density based on the density of the minerals targeted for separation. Once coal is submerged in the medium, it either floats or sinks, and specialised equipment is then used to separate the floats from the sinks. This operational logic is used extensively in the DMS Plant with the primary purpose of concentrating the export and middling product streams and generating the discard stream.

According to Legault-Seguin et al. (2016), DMS has several advantages which include:

- High separation efficiency;
- Simple process control; and
- Simple machinery requirements.

The 2 360 t/h Phola DMS Plant represented a new era of large plant in the Witbank coalfield (Cresswell, 2010). The plant consisted of five main sections: the coarse low gravity (Figure 3.8), smalls low gravity, high gravity, fine coal, and slimes sections. The plant was designed to receive a feed coal size of -50 mm, to screen it into coarse and small coal fractions, which are (-50 mm +12 mm) and (-12 mm +0.63 mm) before processing to produce a 27.5 Megajoule per kg (MJ/kg) export product, a 21.5–23 MJ/kg thermal coal middlings product, and a discard stream.

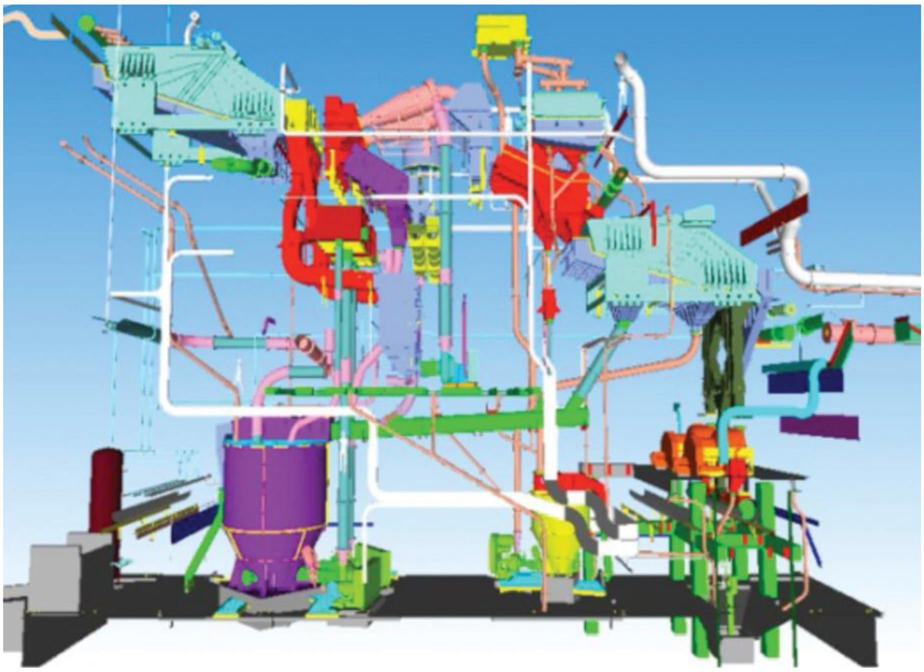


Figure 3.8: Phola Plant – Section through coarse low gravity plant (Cresswell, 2010)

The DMS Plant products are programmed to be deposited onto the product stockpiles to keep track of the total tonnes processed. The DMS and product handling models are simplified representations. Dynamic modelling of the product handling system (from stockpile to rail load-out station) was not conducted because of the high variability in historical train arrival schedules. A static analysis of the rail load-out system was used to establish the system capacity and the capability of the system to process multiple products via the Load-out Station.

Load-out Stations, specifically the flask type, consists of a silo or storage bin, a weigh flask with load cells, a discharge (profile) chute, and a control system (Fletcher, 1997). As each wagon passes underneath the profile chute, photocell switches open the weighflask, and close it after the required mass of material has been discharged into the wagon (Figure 3.9).

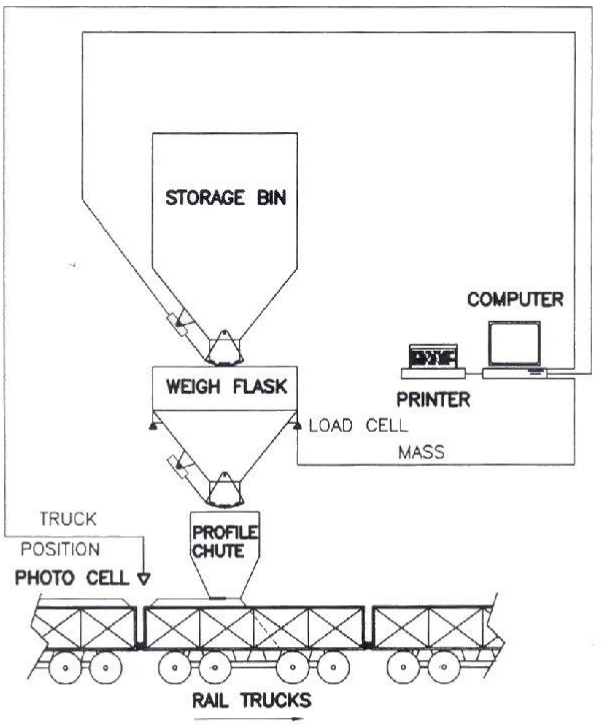


Figure 3.9: Rail Load-out Station (Flask Type) (Fletcher, 1997)

Each of the models were integrated, and the simulation results analysed. The view from the discipline-specific experts and the project review team is that both the approach and the results are acceptable.

The project scope was to target the DMS Plant as the primary constraint or bottleneck. The plant capacity, therefore, determines the sizing of the upstream infrastructure in the materials handling value chain. A plant capacity analysis was conducted which formed the basis of the annual ROM targets which in turn formed the basis for the Mining and BMH system designs (refer to Section 3.8).

3.5 Simulation Assumptions

There were various assumptions made in the model, which include:

- All components, with the exception of the ROM Tip Bin, run at constant rates. Ramp-up and ramp-down rates at start-up and shutdown are not applicable;
- No in-flight material occurs. When material is introduced into a component, it is immediately moved to the next component; and
- Particle Size Distribution (PSD) of material is not applicable.

3.6 Simulation Inputs for the Mining Sub-system

3.6.1 TOC Buffer Management

The use of TOC principles in mine plan development provides the assurance in the LOM extension project feasibility phase that the planned mining schedule is achievable in a practical mining environment. The rules and sizes of the buffers of each of the different mining activities were generated to ensure that no interference occurs between interdependent activities. With active buffer management and sufficient pit length, it is possible for the mine to deliver 5.769 Mtpa. A Monte Carlo Simulation in @Risk was done which aimed to identify the required mining activity buffer capacities or inventory. The level of managerial intervention required during the LOM was also investigated. The existing mine operated on TOC principles. These principles were used to test the probability of success of the new mining schedule and planned equipment production rates.

The current mine process buffers and operating rules were used in the development of the model of the new mine. The simulation logic is based on the principle of a silo level. Each activity was monitored by two silos, one in front, and one at the back of the activity. The silo in front of the truck and shovel activity is filled with material produced by the blasting process. This material will be moved in batches as each block is blasted. The inventory indicator reflects the movement within the silo. The truck and shovel activity extracts material from the preceding silo and fills the next silo with the same amount of material. Volumes of material to be moved and production required per activity was calculated in the mining schedule produced in XPAC (RPM Global) Solutions. The mining schedule has a set of dependency rules in which the relationship between each activity is controlled. All the activities related to the mining operation are linked in the simulation. All silo levels are monitored, and the rules applied to maintain, enhance or stop production are shown in Figure 3.10 and summarised as follows:

- A black condition indicates that inventory levels have reached a stage where other activities are restricted due to high levels and typical coal-bound situations prevail;
- A green (good performance) condition indicates that no intervention is required, and that the activity is self-regulating;
- A yellow (mediocre performance) condition indicates that limited intervention is required because of an increase in start-up inventory, which provides additional time for the activity to normalise. If an increase in inventory does not provide stable results, the catch-up capacity is increased by making use of equipment operating on other activities that have spare capacity. If this is insufficient, additional hours are allocated to the activity. Additional hours are allocated based on the difference between

the maximum hours of the installed equipment units and the required equipment hours calculated by the XPAC Solutions schedule; and

- A red (poor performance) condition indicates that major intervention is required to prevent the stoppage of the overall process. The simulation then treats prevailing yellow buffers as green buffers and allocates all additional capacity to the red buffer. If the red condition cannot be resolved, the buffer level reaches zero, and the simulation is terminated.

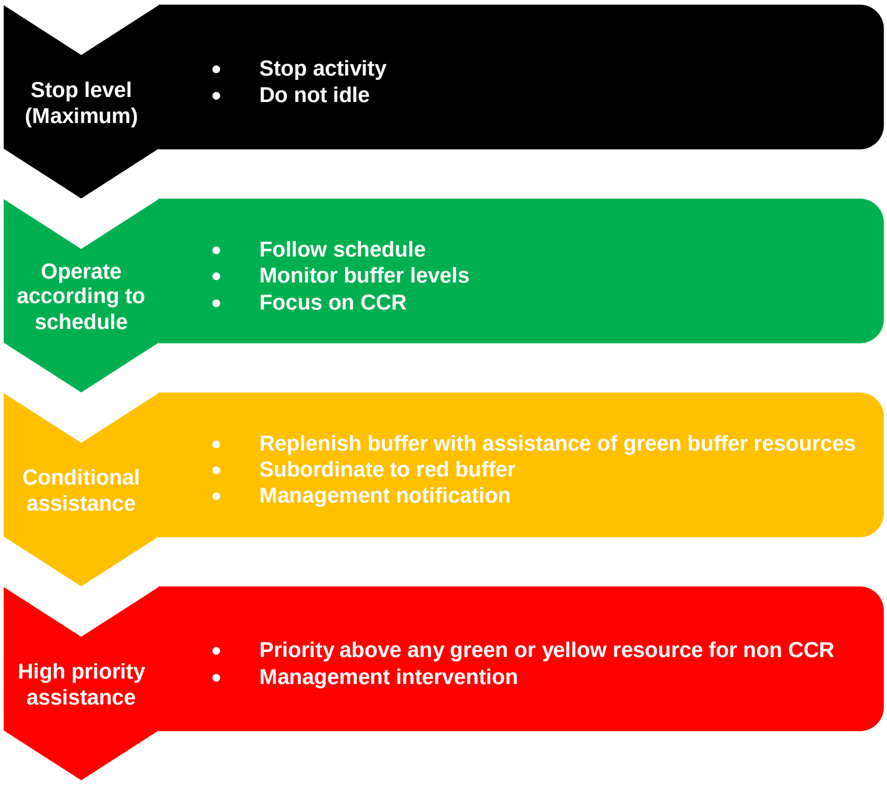


Figure 3.10: Buffer Management Rules

The mining method, as described in Section 1.2, is broken up into eight material-related horizons and 23 activity steps, as shown in Table 3.1.

Table 3.1: Interdependent Mining Activities

No.	Material Horizons	Activity
1.	Topsoil	Removal
2.	Softs	Pre-strip - Truck and Shovel
3.	Hard Burden	Drilling - Expose No. 4 Seam
4.	Hard Burden	Blasting - Expose No. 4 Seam
5.	Hard Burden	Truck and Shovel - Expose No. 4 Seam
6.	No. 4 Seam	Coal Drilling
7.	No. 4 Seam	Coal Blasting
8.	No. 4 Seam	Truck and Shovel
9.	Hard Inter Burden	Pre-split Drilling - Expose No. 2 and 1 Seam
10.	Hard Inter Burden	Drilling - Expose No. 2 and 1 Seam
11.	Hard Inter Burden	Blasting - Expose No. 2 and 1 Seam
12.	Hard Inter Burden	Dozing - Expose No. 2 and 1 Seam
13.	Hard Inter Burden	Truck and Shovel - Expose No. 2 and 1 Seam
14.	No. 2 Seam	Coal Drilling
15.	No. 2 Seam	Coal Blasting
16.	No. 2 Seam	Truck and Shovel
17.	Parting	Drilling
18.	Parting	Blasting
19.	Parting	Truck and Shovel - P1 only
20.	Parting	Dozing - P1 Only
21.	No. 1 Seam	Coal Drilling
22.	No. 1 Seam	Coal Blasting
23.	No. 1 Seam	Truck and Shovel

The simulation model used the mine production figures of the XPAC Solutions model and a set of PERT probability distributions. The PERT distribution is widely used in the mining industry to represent the probability of production. The PERT probability distributions were derived from real-time operational data obtained from the current operation which describes the daily Direct Operating Time (DOT) per piece of equipment. The probability distributions aim to mimic the typical behaviour of each equipment type. Mining equipment has a fluctuating production output due to availability, dependency on other equipment, and operational conditions.

Mining processes are classified as either continuous (for example, dozing) or batch type (for example, drill and blast). In cases where two processes function as a unit, the system's capacity is equal to the lowest capacity of either unit. The truck and shovel fleet were simulated as separate overburden and separate coaling fleets. Figure 3.11 represents typical input data obtained from the current operation for the haul trucks. The graph indicates the average, minimum and maximum percentage of DOT tallied during each specific month over the year 2014 for the haul truck fleet.

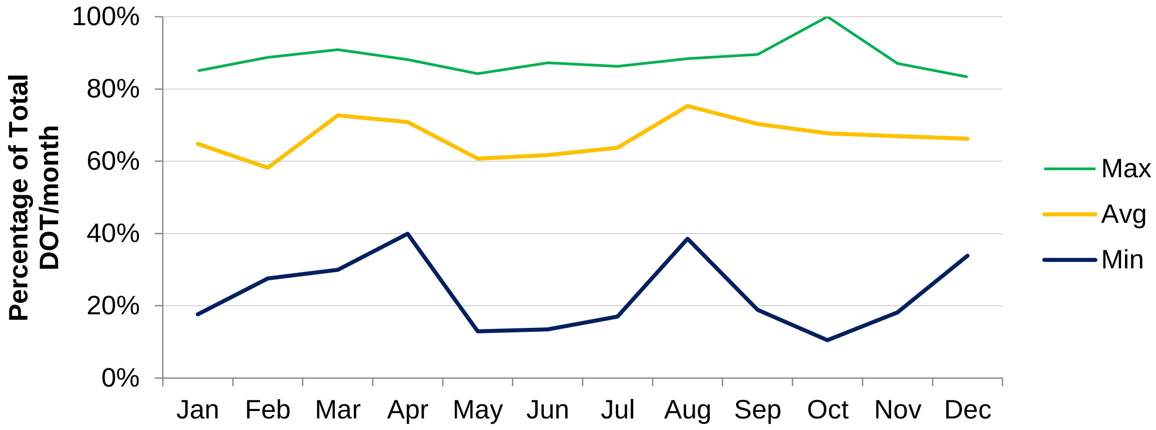


Figure 3.11: Truck DOT (2014)

The minimum, average and maximum percentages have been converted to normalised data by setting the average equal to one. The maximum performance for January is then limited to 129% of the average, and the minimum is limited to 39% of the average. The probability of occurrence was calculated using a PERT distribution with a maximum of 129%, average of 100%, and minimum of 39%. Figure 3.12 indicates the PERT distribution for January 2014.

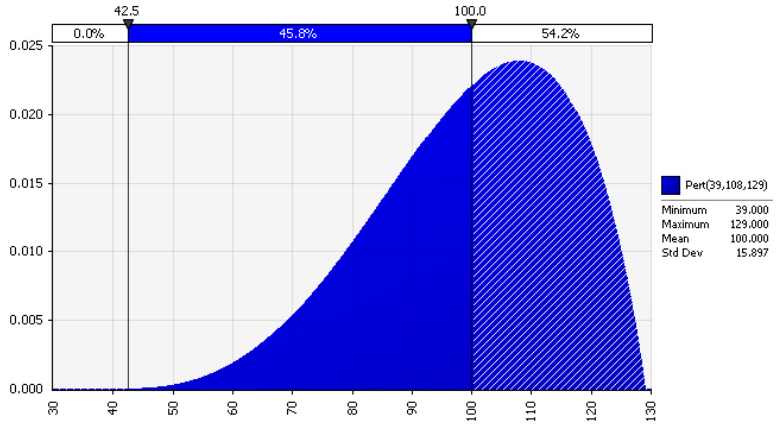


Figure 3.12: Overburden Haul Trucks Probability Distribution for January 2014

From Figure 3.12, it can be seen that 54.2% of the days per month will have higher values than the average, and 45.8% of the days will have lower values than the average. The mode (most likely value) is 108%, which is the peak of the graph.

Unique monthly DOT probability distributions for each of the equipment types were calculated and used in the simulation. The DOT for each production day of January was then calculated by multiplying the average required operating hours per day for January with the specific seeding result. A seeding is one part of the simulation where every distribution function is populated with a unique value according to the shape of the applicable distribution. During a full-scale simulation, 5 000 seedings were performed and recorded. The simulation calculated the buffer space required to ensure that no interference occurs between interdependent activities. The production outputs of all the mining activities were simulated. This was conducted by multiplying the scheduled tempo with the recalculated daily DOT.

The probability of successful production was evaluated in terms of pit length. The probability of success is defined as the ability to manage the schedule without managerial interventions, and it is categorised into three levels as follows:

- Green. For 80% of the time, the schedule is governed by TOC rules to achieve at least 90% of the scheduled production.
- Yellow. For 60% of the time, the schedule is governed by TOC rules to achieve at least 90% of the scheduled production.
- Red. For 30% of the time, the schedule is governed by TOC rules to achieve at least 90% of the scheduled production.

The plan was to design the mine to perform between the green and yellow levels, but not at the red level. All activities related to topsoil, soft overburden, pre-split and portions of the hard overburden drilling should be conducted at least one strip ahead of the production strip. Provision for blast block inventory should be made rather than blasted coal inventory. The blasted coal inventory should not be less than four days of production calculated per individual seam. If any of the buffer levels reach the maximum capacity level, the operation on that activity should be stopped and equipment allocated to other activities, rather than continuing at a low tempo. The detailed levels pertaining to the red, yellow and green buffer levels which were calculated in Palisade's @Risk software are shown in Table 3.2.

Table 3.2: Proposed Detail Buffer Lengths

Material Horizons	Activity	Red Buffer (m)	Yellow Buffer (m)	Green Buffer (m)
Topsoil	Removal	1 750	2 500	4 000
Softs	Pre-strip - Truck and Shovel	1 280	2 500	4 000
Hard Burden	Drilling - Expose No. 4 Seam	500	750	1 800
Hard Burden	Blasting - Expose No. 4 Seam	500	750	1 440
Hard Burden	Truck and Shovel - Expose No. 4 Seam	330	600	1 440
No. 4 Seam	Coal Drilling	500	750	1 440
No. 4 Seam	Coal Blasting	405	750	1 440
No. 4 Seam	Truck and Shovel	405	750	1 080
Hard Inter Burden	Pre-split Drilling - Expose No. 2 and 1 Seam	575	900	4 800
Hard Inter Burden	Drilling - Expose No. 2 and 1 Seam	650	1 200	1 800
Hard Inter Burden	Blasting - Expose No. 2 and 1 Seam	650	1 200	1 440
Hard Inter Burden	Dozing - Expose No. 2 and 1 Seam	180	300	1440
Hard Inter Burden	Truck and Shovel - Expose No. 2 and 1 Seam	255	450	1 080
No. 2 Seam	Coal Drilling	500	850	1 440
No. 2 Seam	Coal Blasting	500	850	1 440
No. 2 Seam	Truck and Shovel	405	750	1 080
Parting	Drilling	575	900	1 080
Parting	Blasting	575	900	1 080
Parting	Truck and Shovel - P1 Only	180	300	720
Parting	Dozing - P1 Only	120	180	720
No. 1 Seam	Coal Drilling	120	180	720
No. 1 Seam	Coal Blasting	120	180	720
No. 1 Seam	Truck and Shovel	120	180	720

3.6.2 Coaling Operating Time (Hitachi EX3600 Excavator)

The short-term coaling plan was based on the number of days the BMH system was available and scheduled over 305 days of the year (Table 3.3).

Table 3.3: BMH Operating Days per Year

No.	Description	Days	Percent Base	Comments	Calculation
A	Calendar Time	365	100%		
B	Public Holidays	13	4%		
C	Uncontrollable Events	20	5%	Rain delays	
D	Total Controllable Time	332	91%		A – B – C
E	Normal Scheduled Maintenance	20	5%	9 hours once a week	(365 ÷ 7) x 9 ÷ 24
F	Extended Scheduled Maintenance	2	1%	12 hour shut every 4 weeks	(365 ÷ 28) x 3 ÷ 24
G	Annual Scheduled Maintenance	5	1%	5-day annual shut	
H	Total Scheduled Maintenance	27	7%		E + F + G
I	Available Days	305	84%		D – H

The categories referred to in Table 3.3 are explained below.

Calendar Time (A)

The total days per year, which was 365 days.

Public Holidays (B)

The average number of public holidays over 2014 and 2015, which was 13 days.

Uncontrollable Events (C)

This allocation represents an estimate of 20 days lost due to adverse weather conditions (rain).

Total Controllable Time (D)

Controllable Time was calculated by subtracting Public Holidays and Uncontrollable Events from Calendar Time.

Normal Scheduled Maintenance (E)

The mine conducted scheduled maintenance on the BMH system every week for a duration of nine hours. This time allocation was calculated as:

Normal Scheduled Maintenance $= (365 \div 7) \times 9 \div 24$

$= 20 \text{ days}$

Extended Scheduled Maintenance (F)

Every fourth week, the mine extended planned maintenance by three hours. This time allocation was calculated as:

Extended Scheduled Maintenance $= (365 \div 28) \times 3 \div 24$

$= 2 \text{ days}$

Annual Scheduled Maintenance (G)

Once a year, the mine conducted an annual five-day maintenance shut.

Total Scheduled Maintenance (H)

This category represents the sum of Normal, Extended and Annual Scheduled Maintenance hours.

Available Days (I)

The Available Days were calculated by subtracting the Total Scheduled Maintenance from Calendar Time. The hours available for the mine Hitachi EX3600 Excavator were calculated (Table 3.4) using historical data from 2014, 2015 and 2016 (Quarter 1).

Table 3.4: Mining COT Calculation

No.	Description	Hours	Percent Base	Calculation
A	Total Time	8 760	100%	365 x 24
B	Not Scheduled to Produce	309	4%	12.88 x 24
C	Uncontrollable Events	566	6%	23.57 x 24
D	Controllable Time	7 885	90%	A – B – C
E	Unscheduled Maintenance	595	7%	Calculated from historical data
F	Scheduled Maintenance	794	9%	Calculated from historical data
G	Operational Stops	232	3%	Calculated from historical data
H	Uptime	6 264	72%	D – E – F – G
I	Operational Indirect	216	2%	Calculated from historical data
J	Operational Delays (Unplanned)	247	3%	Calculated from historical data
K	Operational Delays (Planned)	352	4%	Calculated from historical data
L	Unclassified	246	3%	Calculated from historical data
M	DOT	5 202	59%	H – I – J – K – L
N	Use of 994 During Maintenance	596	7%	Allowance
O	COT	5 798	66%	M + N

The mining time model (waterfall graph format) was developed from Table 3.4 for the Hitachi EX3600 Excavator (Figure 3.13).

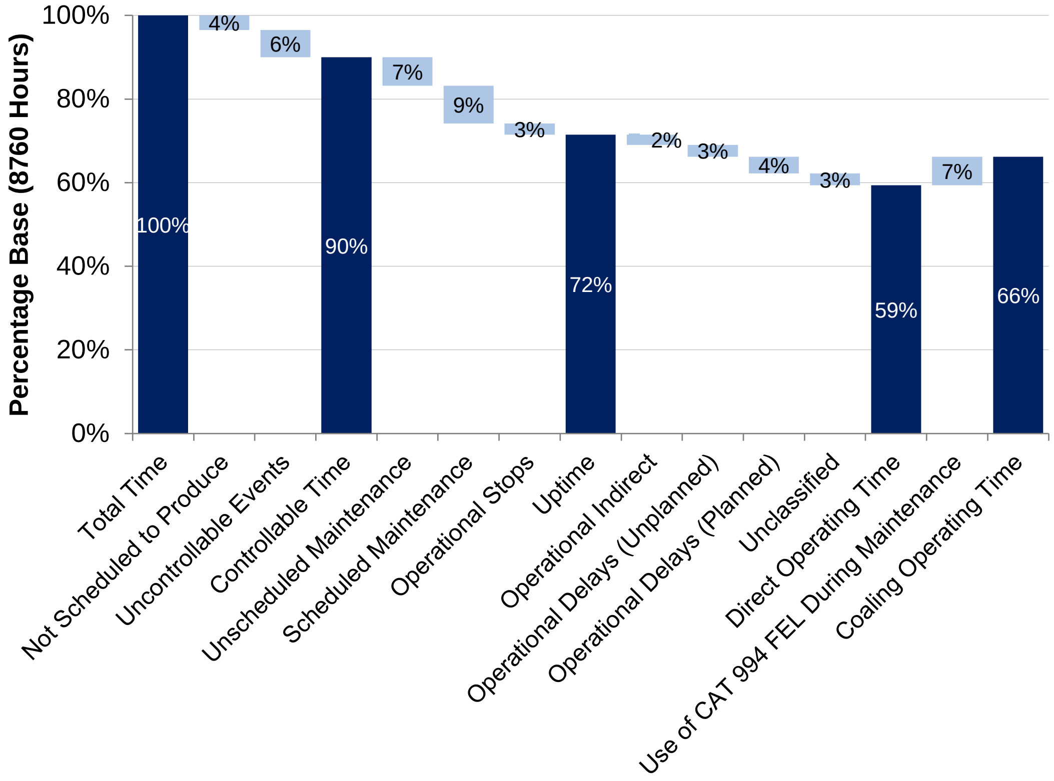


Figure 3.13: Mining Time Model (Hitachi EX3600 Excavator)

The categories referred to in Figure 3.13 are explained below:

Total Time (A)

This was the Total Calendar Time per year: *365 x 24 = 8 760 hours*

Not Scheduled to Produce (B)

This time is defined as Public Holidays or Non-Production Shifts. For 2014 and 2015, the number of public holidays on average equated to 12.88 days due to some public holidays falling on a Sunday.

These hours were, therefore: *Not Scheduled to Produce* *= 12.88 x 24*

= 309 hours

Uncontrolled Events (Weather Days) (C)

These are days on which the coal trucks did not run due to mist, muddy or slippery conditions, and water in the pit. Labour-related disruptions also form a portion of this time (3.57 days). These days equated to 23.57 days

(566 hours) per year. G2 was programmed to impose the impact of 20 rain days per year on the mining fleet and the system in general.

Controllable Time (D)

The Controllable Time was calculated by subtracting Not Scheduled to Produce and Uncontrollable Events from Total Time.

Unscheduled Maintenance (E)

This category covers the time taken to fix the machine when breakdowns were experienced. This time was calculated to be 595 hours per year.

Scheduled Maintenance (F)

This time was allocated to planned maintenance of the machine, which was calculated as 794 hours per year.

Operational Stops (G)

This time includes breakdowns, replacement of ground engaging tools, and trucks not running the route as scheduled. Diesel refuelling and process interruptions make up the bulk of this time. This time was calculated to be 232 hours per year.

Uptime (H)

The Uptime was calculated by subtracting Unscheduled Maintenance, Scheduled Maintenance and Operational Stops from Controllable Time.

Operational Indirect (I)

This category is the time allocated to shift changes, calculated at 216 hours per year.

Operational Delays (Unplanned) (J)

This time equates to the ad-hoc delays experienced on the mine, calculated at 247 hours per year.

Operational Delays (Planned) (K)

This time was allocated to pre-shift checks conducted on the machine, calculated to be 352 hours per year.

Unclassified (L)

This was the time when trucks were unavailable and could not be loaded for a variety of reasons. This time averaged 246 hours per year.

Direct Operating Time (M)

DOT was calculated by subtracting Operational Indirect, Operational Delays (Unplanned), Operational Delays (Planned) and Unclassified from Uptime.

Use of CAT 994 FEL (N)

An allowance was made for the use of the CAT 994 Front End Loader (FEL), a spare machine in the new mine plan, during periods when the excavator was being maintained. The assumption was that the CAT 994 FEL would be available for 60% of the unscheduled maintenance and 30% of the operational delays (unplanned) of the coaling excavator, together with 166 hours that stem from the difference in planned maintenance between the excavator and the BMH system (Figure 3.13 and Figure 3.14). This allowance equates to 596 hours per year.

3.6.3 Coaling Operating Time (Komatsu 730e Truck)

The mining hours per year were limited to 5 798 hours, dictated by the available time for the Hitachi EX3600 Excavator (Table 3.4). The achievable production (t/h) per truck does not need to be calculated for the specific simulation approach used. The time per day available to the trucks for coaling was calculated and used in the development of the mine variable feed rate input file, which was used by the G2 Simulation (Section 3.6.4). For 2014, 2015 and 2016 Quarter 1, the best uptime the trucks achieved was 20.4 hours in one day. It was difficult to separate the coal from the overburden truck information because each truck was used interchangeably. A maximum DOT of 21 hours per day for a dedicated fleet of coal trucks was used. Thus, three hours of no coal per day (1.5 hours at the start and end of each 12-hour shift) was incorporated into the mining input file in the G2 simulation. The total hours lost to mining shift changes was calculated as follows:

Mining shift changes = 3 hours per day @ 305 days = 915 hours

In the G2 simulation, 915 lost hours were scheduled on the mining truck fleet only, which was a consequential lost time event on the BMH system (Figure 3.14).

3.6.4 Feed Rate to the ROM Tip

The mining operation is a single loading fleet, with a maximum loading rate of 1 263 t/h. The maximum loading rate was calculated in Talpac (RPM Global), and this is the rate that could be achieved by one excavator when fully trucked (four trucks). The engineering experts on the team were comfortable using this rate going forward. Trucks were used interchangeably between the CAT 994 FEL and the Hitachi EX3600 Excavator. The mine did not record the allocation of trucks to each specific excavator or loader. It was, therefore, not possible to verify from historical operational data what the achievable mine production was for each of the excavators and the loader. Therefore, the performance of the Hitachi EX3600 Excavator and the CAT 994 FEL was assumed to be the same. The input file for the G2 simulation was generated in Palisade's @RISK software. Palisade's @RISK software generated 10 sets, each containing 1 000 iterations of typical production days in each set. Each day consisted of random feed rates within a typical 21-hour day experienced on the mine. The feed rate was programmed not to exceed 1 263 t/h and to fall within a feed to ROM Tip PERT probability distribution which was generated using historical data.

Palisade's @RISK software automatically incorporated unplanned stops (hours with zero tonnes) per day using historical Mean Time To Repair (MTTR) data for the excavators from 2014 to 2015. Palisade's @RISK software was programmed to select 365 days within each set of 1 000 days which were assessed prior to input into the G2 simulation. The 365 days within a specific set that were likely to yield the average yearly scheduled production of 6 Mtpa were selected for input into the G2 simulation. To integrate the Palisade's @RISK software model outputs into the G2 model, a variable production input was incorporated into the G2 model, in accordance with the variable mining feed.

The mining input file provided probable mine feed distributions per day, for a period of 365 days. The G2 simulation then discounted the mining feed inputs, depending on ROM Tip availability, utilising the following discounting factors, which led to a total of 88 days lost over the year:

- Rain delays (20 days in total simulated over the year);
- Annual five-day shut;
- Public holidays (13 days in total simulated to occur on actual annual date);
- BMH Scheduled maintenance events (21 days in total simulated over the year); and
- BMH Unscheduled maintenance events (29 days in total simulated over the year).

Table 3.5 shows the potential mine production outcomes based on the capability of the coal mining fleet which was calculated in Palisade's @RISK software. P(1) represents the lowest (1%) probability of success and P(95) represents the highest (95%) probability of success. Over the 305 days the BMH was available (Table 3.3), the peak coaling rate of 1 263 t/h was required to be achieved for 17.357 hours per day to produce 21 922 t.

Table 3.5: Potential Production of Mining Operation

Probability (Risk)	Tonnes Per Year (21-hour day for 305 days)	Tonnes Per Day	Tonnes Per Hour (21 hours)
Min.	4 344 102	14 243	-
Max.	7 254 785	23 786	1 263
P(95)	6 003 534	19 684	937
P(90)	6 285 400	20 608	981
P(80)	6 440 498	21 116	1 006
P(70)	6 547 631	21 468	1 022
P(60)	6 609 891	21 672	1 032
P(50)	6 686 340	21 922	1 044
P(40)	6 769 197	22 194	1 057
P(30)	6 823 713	22 373	1 065
P(20)	6 909 351	22 654	1 079
P(10)	7 009 749	22 983	1 094
P(5)	7 075 959	23 200	1 105
P(1)	7 214 419	23 654	1 126

At a 95% confidence level (P95), the average production over a 21-hour shift was calculated to be 937 t/h, resulting in a production of 19 684 t per day. The yearly tonnage calculation provides an indication but could be zero for any specific day. The simulation indicates that over 305 days, the coal that could be delivered to the ROM Tip could range between 14 243 t and 23 786 t per day, with the most likely production being 19 684 t per day.

3.7 Simulation Inputs for the BMH Sub-system

3.7.1 DOT

The DOT for the BMH system from the ROM Tip through to the Raw Coal Stockpile was calculated as described in Table 3.6.

Table 3.6: BMH DOT Calculation

No.	Description	Hours	Percent Base	Calculation
A	Total Time	8 760	100%	365 x 24
B	Not Scheduled to Produce	312	4%	12.88 x 24
C	Uncontrollable Events	480	5%	20 x 24
D	Controllable Time	7 968	91%	A – B – C
E	Unscheduled Maintenance	693	8%	Calculated from historical data
F	Scheduled Maintenance	628	7%	Calculated from mine maintenance schedule
G	Operational Stops	88	1%	Simulation output
H	Uptime	6 559	75%	D – E – F – G
I	Operational Indirect	915	10%	Mining Shift Changes
J	Operational Delays (Unplanned)	0	0%	
K	Operational Delays (Planned)	0	0%	
L	Unclassified	0	0%	
M	DOT	5 644	64%	H – I – J – K – L

The BMH time model (waterfall graph format) was developed from Table 3.6 (Figure 3.14).

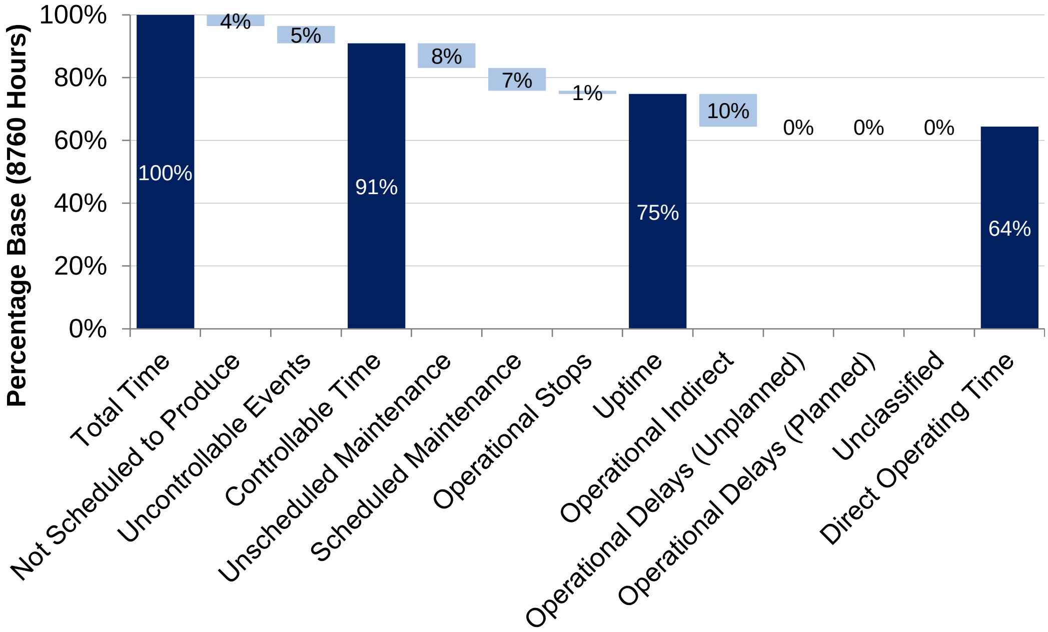


Figure 3.14: BMH Time Model

The categories referred to in Figure 3.14 are explained below.

Total Time (A)

This was the total calendar time per year: *365 x 24 = 8 760 hours*

Not Scheduled to Produce (B)

Thirteen public holidays per year were taken into consideration, which equated to 312 hours per year. This corresponds to the public holidays accounted for in the mining time model in Section 3.6.2.

Uncontrollable Events (C)

Uncontrollable events, which consist of weather days, were taken into consideration in the available hours calculation. There were 20 days allocated for uncontrollable events which were consequential losses on the BMH system.

Controllable Time (D)

The Controllable Time was calculated by subtracting Not Scheduled to Produce and Uncontrollable Events from Total Time.

Unscheduled Maintenance (E)

This category refers to time lost due to equipment failures. This time was made up of Mean Time To Failure (MTTF) and MTTR equipment data. Historical information obtained from the current mine was used to develop MTTF and MTTR probability distribution functions for each piece of equipment, which are shown in Table 3.7. G2 used the distributions to calculate the annual unscheduled maintenance hours.

Table 3.7: Coal Mine A MTTF and MTTF Data

Equipment Name	MTTF		MTTR		
	PDF	Hours	PDF	Hours	Availability
Flight Bar Feeder*	Normal	150	Triangular	1	0.993
Flight Bar Feeder**	Normal	4 380	Triangular	48	0.989
Primary Sizer	Normal	170	Triangular	0.8	0.995
Secondary Sizers	Normal	150	Triangular	0.9	0.994
Primary Receiving Conveyor	Normal	100	Triangular	1.67	0.984
Overland Conveyor*	Normal	100	Triangular	2	0.984
Overland Conveyor**	Normal	4 380	Triangular	24	0.995
Tie-in Conveyor	Normal	100	Triangular	1.67	0.984
Reclaimer	Normal	4 380	Triangular	48	0.989
Vibrating Screen	Normal	80	Triangular	0.87	0.989

*Short Breakdowns
** Long Breakdowns

Scheduled Maintenance (F)

The mine had a planned maintenance schedule in place for the existing plant. The maintenance schedule for the additional bulk materials handling plant was discussed and agreed upon with mine operational personnel (Table 3.3).

Operational Stops (G)

Operational stops consist of equipment stoppages due to upstream or downstream equipment failures, and stockpiles full or empty. This was simulated within the G2 environment using the probability distribution functions as described under "Unscheduled Maintenance (E)".

Uptime (H)

The Uptime was calculated by subtracting Unscheduled Maintenance, Scheduled Maintenance and Operational Stops from Controllable Time.

Operational Indirect (I)

This category was defined as time allocated to shift changes, which equated to 915 hours.

DOT (M)

DOT was calculated by subtracting Operational Indirect, Operational Delays (Unplanned), Operational Delays (Planned) and Unclassified from Uptime.

3.7.2 Feed Rate to Raw Coal Stockpile

The feed rate in the mechanical design basis of the BMH is summarised below:

- Nominal Production = 1 022 t/h. This was the average feed rate that could be sustainably supported by the system.
- Peak Production = 1 263 t/h. The system was designed to run at a peak rate for limited durations for the purposes of catch-up after potential upset conditions.

The feed rate from the ROM Tip to the Raw Coal Stockpile was set at the peak of 1 263 t/h in the G2 simulation for both the 5.769 Mtpa and the 6.484 Mtpa scenarios.

3.8 Simulation Inputs for the DMS Plant Sub-system

3.8.1 DOT

The DOT for the DMS Plant was calculated as described in Table 3.8 using historical downtime data (2011 to 2015). The downtimes from the initial years of Coal Mine A's operation are not reported in the current time model format and judgement was used to allocate the reported downtime to the appropriate downtime categories. The DMS time model (waterfall graph format) was developed from Table 3.8 (Figure 3.15).

Table 3.8: DMS DOT Calculation

No.	Description	Hours	Percent Base	Calculation
A	Total Time	8 760	100%	365 x 24
B	Not Scheduled to Produce	288	3%	12 x 24
C	Uncontrollable Events	32	0%	Calculated from historical data
D	Controllable Time	8 440	96%	A – B – C
E	Unscheduled Maintenance	917	10%	Calculated from historical data
F	Scheduled Maintenance	507	6%	Calculated from mine maintenance schedule
G	Operational Stops	199	2%	Simulation output
H	Uptime	6 817	78%	D – E – F – G
I	Operational Indirect	117	1%	Calculated from historical data
J	Operational Delays (Unplanned)	0	0%	
K	Operational Delays (Planned)	0	0%	
L	Unclassified	0	0%	
M	DOT	6 700	76%	H – I – J – K – L

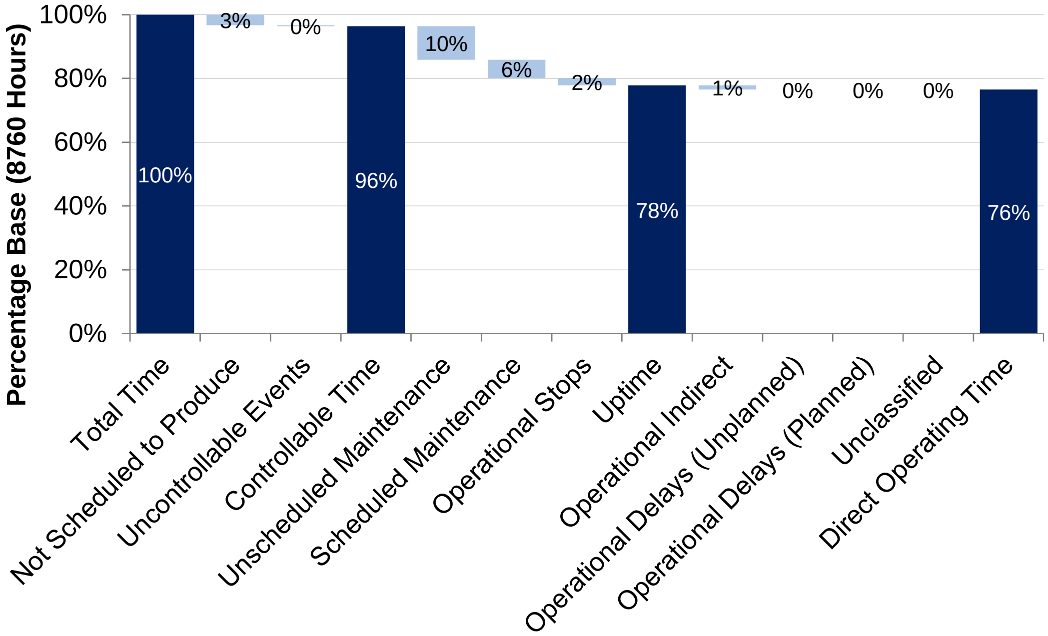


Figure 3.15: DMS Time Model

The categories referred to in are explained below.

Total Time (A)

This was the total calendar time per year: *365 x 24 = 8 760 hours*

Not Scheduled to Produce (B)

There is evidence in the historical data that plant personnel worked on public holidays. In the DMS Time Model, 12 days were allocated to public holidays instead of the 13 days allocated to the BMH and Mining disciplines.

Uncontrolled Events (C)

Historically, the data shows that the plant was not impacted by weather days because of the 45 000 t Raw Coal Stockpile before the DMS Plant. For this reason, only 32 hours were allocated to this category.

Controllable Time (D)

The Controllable Time was calculated by subtracting Not Scheduled to Produce and Uncontrollable Events from Total Time.

Unscheduled Maintenance (E)

Historical DMS Plant breakdown information was used to develop a statistical Weibull distribution which was input into the G2 simulation and used to simulated failure events. The data was arranged into MTTF and MTTR data sets. A concern at the time was that historical, unplanned maintenance potentially does not reflect the true unplanned maintenance performed. This is due to opportunistic maintenance being conducted during no-coal events when the plant was on stop and not logged as such but as no-coal. The MTTF data was adjusted to simulate, on average, an additional 168 hours of unplanned maintenance. This additional unplanned maintenance was expected to occur as less opportunistic maintenance will be possible if the DMS Plant receives the planned volumes of coal from the new resource. The total unplanned maintenance hours calculated by G2 equated to 917 hours per annum.

Scheduled Maintenance (F)

The mine had the following planned maintenance schedule in place for the DMS Plant:

- 9 hours once a week = 469 hours
- 12 hour shut every first week of a month = 39 hours
- Total = 507 hours

Operational Stops (G)

A total of 199 hours was allocated to operational stops. These hours were reported as DOT by the dynamic simulation, above the 6 700 hours required to attain the original design basis DOT. The hours were allocated to account for expected operational stops that were not reported in the actual downtime data analysed. It appears that operational stops were masked by no-coal events. The 199 hours represent a potential positive aspect in the planned DOT and, therefore, the expected Feed To Plant (FTP) per annum.

Uptime (H)

The Uptime was calculated by subtracting Unscheduled Maintenance, Scheduled Maintenance and Operational Stops from Controllable Time.

Operational Indirect (I)

This category refers to no-coal events. Discussions were held with the operations team who stated that no-coal events were masked by extended planned maintenance during 2014 and 2015. Further maintenance was completed due to no coal being available on completion of maintenance. It was also identified that production start-up was delayed because the mine took advantage of low electricity tariffs after 10:00 pm. Coal Mine A achieved substantial savings in electricity costs using this approach. Extended planned maintenance hours and late start-up hours were considered in the no-coal hours calculation, which yielded 177 hours per annum.

DOT (M)

DOT was calculated by subtracting Operational Indirect, Operational Delays (Unplanned), Operational Delays (Planned) and Unclassified from Uptime.

3.8.2 Feed Rate to DMS Plant

The DMS Plant had a production capacity of 6 Mtpa, 896 t/h Air Dry (ad), which was based on the previous ore reserve metallurgical characteristics. The ore from the new reserve was different to the previous ore reserve characteristics (lower yields and coarser PSD). Due to the differences in characteristics between the two reserves, the achievable production of the existing plant for the new reserve was lower than that of the previous reserve. The new mine was designed to target the higher yielding coal blocks, which reduced the overall yield variance (yield envelope). The target product qualities remained unchanged (5 800 kilocalories per kg Net as Received (NAR) ad primary product and 21.6 MJ/kg ad middlings product). A capacity analysis was conducted which yielded the results summarised in Table 3.9. This formed the basis for the ROM targets.

Table 3.9: Feed To Plant (New Reserve) Scenarios

Probability (Risk)	FTP (t/h ad)	Annual tonnes (ad)	FTP (t/h @ 5% moist.)	Annual Tonnes (@ 5% moist.)
Plant Maximum	922	6 175 000	968	6 484 000
Average Annual	820	5 494 000	861	5 769 000
Low FTP Possibility p2.5	748	5 012 000	785	5 259 500

The Raw Coal Stockpile Reclaimer was designed for a reclaim rate of 1 350 t/h, which did not correlate with the DMS Plant capacity (Table 3.9). Performance tests were completed during which it was established that the Reclaimer could only deliver 948 t/h, as measured on the DMS Plant Feed Conveyor belt scale. This was significantly below the original design capacity, however, under normal conditions, the Reclaimer recovery rate could exceed the required nominal FTP of 861 t/h. With reference to Table 3.9, the feed rate from the Raw Coal Reclaim Conveyor to the DMS Plant was set at 861 t/h for the 5.769 Mtpa scenario and 968 t/h for the 6.484 Mtpa scenario in the G2 simulation.

3.9 G2 Simulation Outputs

3.9.1 Buffer Silo Size Validation

A Buffer Silo was added into the system between the Primary Receiving Conveyor and the Overland Conveyor (Figure 3.16), and the G2 simulation was run with Buffer Silos of different size configurations.

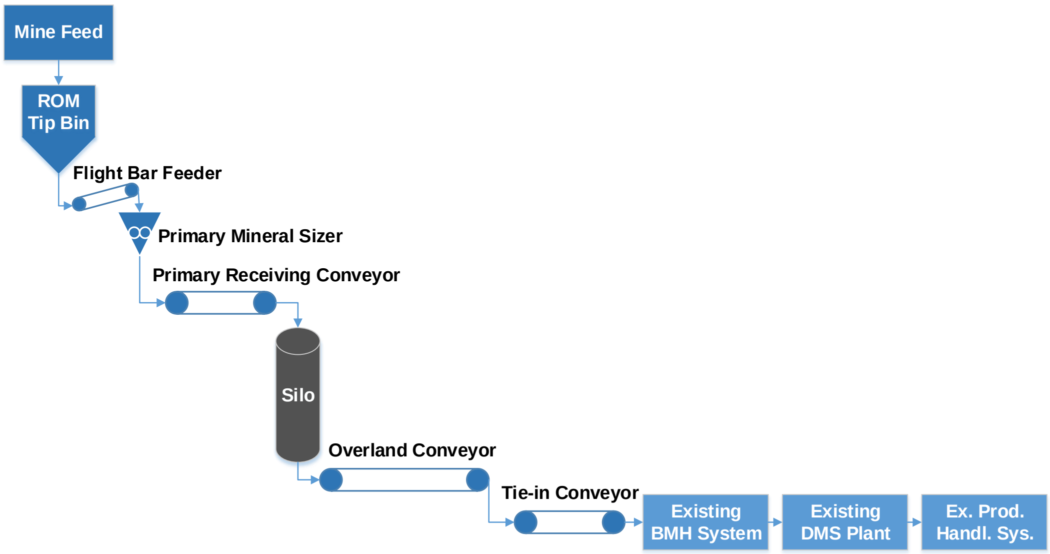


Figure 3.16: BMH System with Buffer Silo Included

From the results of the G2 simulation, it was identified that various Buffer Silo sizes did not contribute to increased annual production tonnages, namely, 30 000 t with a 1 000 t Silo, 40 000 t with a 2 000 t Silo, 20 000 t with a 3 000 t Silo, and 30 000 t with a 6 000 t Silo (Figure 3.17). The difference between the achievable annual production with no Silo and Silos of different sizes was negligible.

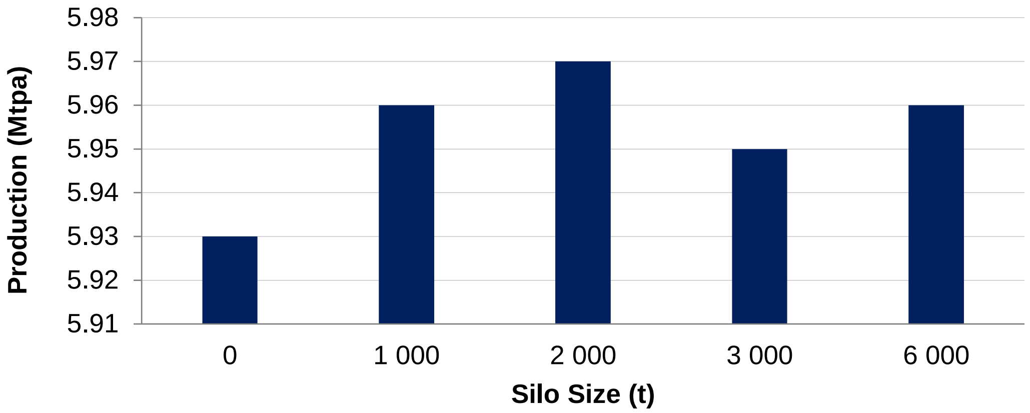


Figure 3.17: Production (Mtpa) vs. Buffer Silo Size - G2 Simulation Results

The variances in production for the different silo sizes are comparable to the statistical variance (± 30 000 t) of the G2 model (Figure 3.18).

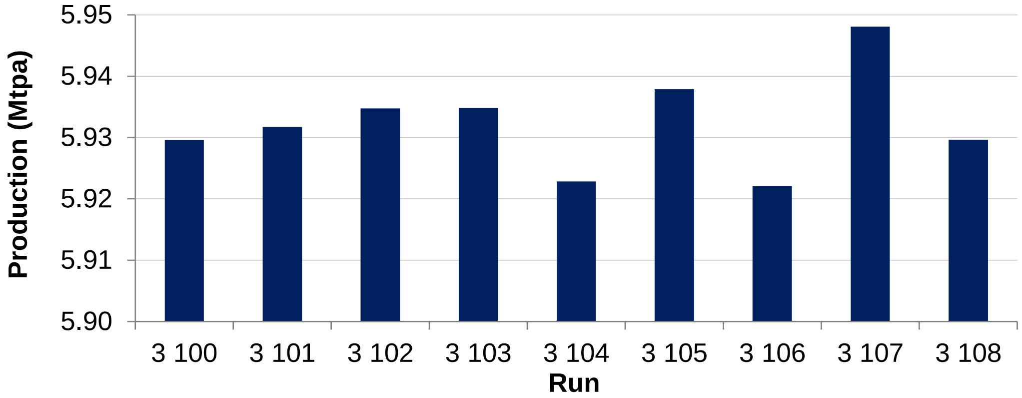


Figure 3.18: G2 Output Variability

A statistical variance of less than 1% was achieved, which provides confirmation that the G2 model was stable and consistent.

3.9.2 Raw Coal Stockpile Level

The Raw Coal Stockpile level (based on a live maximum capacity of 45 000 t) was analysed in the G2 simulation with and without a 3 000 t Buffer Silo. Figure 3.19 shows the Raw Coal Stockpile level without a 3 000 t Buffer Silo and Figure 3.20 shows the Raw Coal Stockpile level with a 3 000 t Buffer Silo.

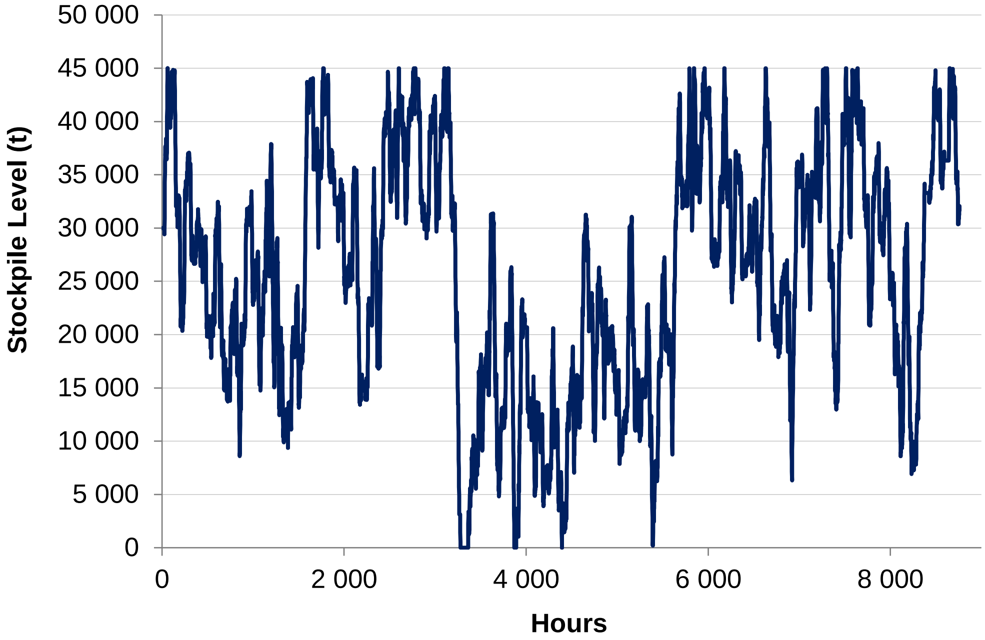


Figure 3.19: Raw Coal Stockpile Level (DMS 861t/h, 5.769 Mtpa) – No Silo

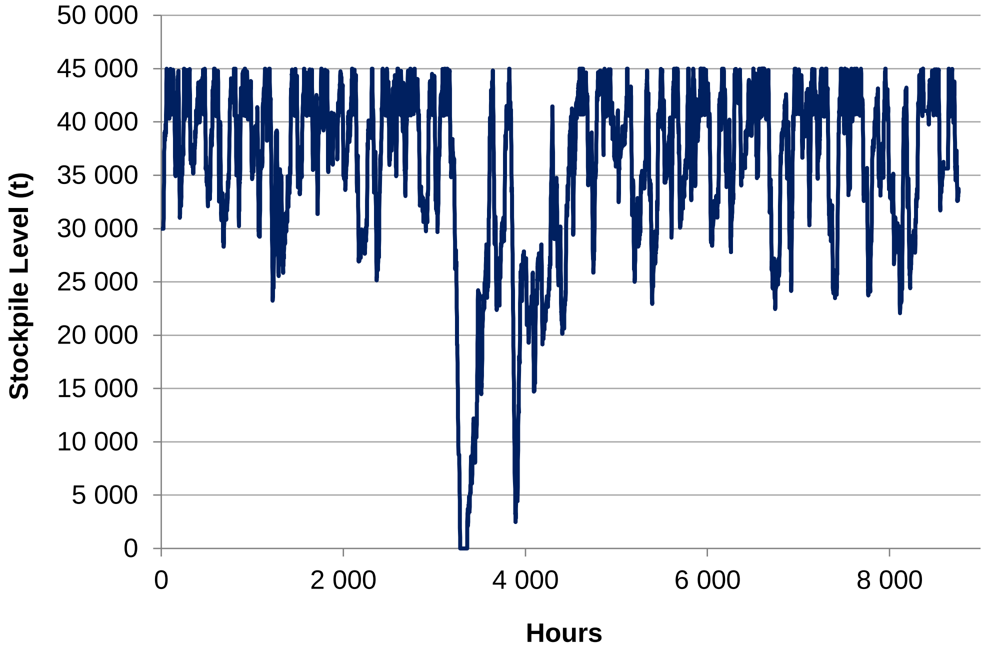


Figure 3.20: Raw Coal Stockpile Level (DMS 861t/h – 5.769 Mtpa) – With a 3 000 t Silo

There was a negligible difference between the level of the Raw Coal Stockpile with and without a 3 000 t Buffer Silo. The current Raw Coal Stockpile capacity was sufficient to allow the annual target of 5.769 Mtpa to be achieved without a Silo. The full stockpile capacity is 60 000 t, but there was approximately 15 000 t of “stagnant” stockpile capacity required to sustain plant feed rates and to reduce fragmentation. The 0 t level in Figure 3.19 and Figure 3.20 represents 15 000 t.

Many coal mining operations make use of Silos. Each of these systems has different processing capabilities, and although there are similarities, each system is unique. For this reason, benchmarking was not conducted to validate the decision on whether to include a Silo or not. The G2 simulation, being an acceptable industry standard, was set-up with actual plant information such that it could accurately mimic the proposed system. The outputs of the G2 simulation were accepted by all stakeholders.

3.9.3 Annual Production Targets

Two scenarios (Table 3.10 and Table 3.11) were generated in the G2 simulation to establish whether the annual targets of 5.769 Mtpa and 6.484 Mtpa can be achieved. Each scenario was run 10 times. The marginal variance between the respective runs was within the variability of the G2 model.

Table 3.10: 5.769 Mtpa Target Scenario

Scenario	Mine Feed (Mtpa)	DMS Rate (t/h)	BMH Rate (t/h)	Achieved Production (Mtpa)
Base Case	P(95)	861	1 263	5.93
Base Case (3 000 t Silo Incl.)	P(95)	861	1 263	5.95

Table 3.11: 6.484 Mtpa Target Scenario

Scenario	Mine Feed (Mtpa)	DMS Rate (t/h)	BMH Rate (t/h)	Achieved Production (Mtpa)
Base Case	P(70)	968	1 263	6.53
Base Case (3 000 t Silo Incl.)	P(70)	968	1 263	6.70

The results indicate that both the 5.769 Mtpa and 6.484 Mtpa annual targets can be achieved without a 3 000 t Silo. The system could achieve 5.93 Mtpa with a P(95) mine feed, and 6.53 Mtpa with a P(70) mine feed. A further investigation was conducted to determine the potential increase in BMH DOT if a 3 000 t Silo was constructed. The Front End up-time increased by 118 hours due to the Silo “buffering” the nuisance trips on the downstream components. However, there was no guarantee that the mining operation would utilise the 118 additional hours. The cost to construct the Silo is approximately R44 million. This, coupled with no Net Present Value benefit, justifies the elimination of the 3 000 t Silo option.

3.10 Rail Load-Out Station Capacity Analysis

An investigation was conducted to determine if the current BMH and rail load-out station can process the annual product volumes of:

- 2.3 Mtpa Export;
- 1.2 Mtpa Middlings; and
- 0.3 Mtpa Briquettes.

The following was considered in the analysis of the system:

- Existing system capacity constraints;
- Installed capacity of BMH system;
- Historical train arrival variations;
- Historical pre-loading train preparation times and delays;
- Historical train loading times;

- System purge time between different products;
- Total required product switchovers per year;
- Historical post-loading or pre-departure delays; and
- Historical Transnet Freight Rail (TFR) and Coal Mine A train cancellations.

One of the main driving factors in rail load-out systems is the train arrival schedule and the typical variability associated with it. From discussions with operational staff and the analysis of data obtained from the operation, it was established that the current TFR train arrival schedules and train arrival times were highly variable (Figure 3.21).

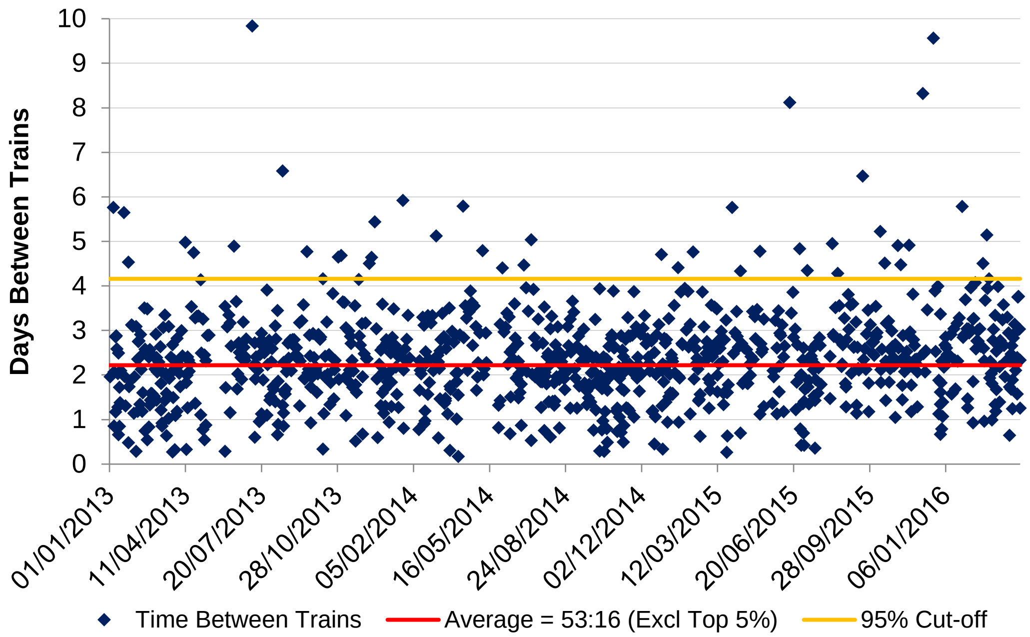


Figure 3.21: Time Between Trains (Excluding Cancelled Trains)

The variability in the data is of such a magnitude that utilising the variability as an input into a dynamic model to establish system capacity would not have yielded reasonable results. Therefore, a static calculation was performed to evaluate the capacity of the system.

3.10.1 Rail Load-out Station Analysis

The static calculation (Table 3.12) considered various inputs associated with the rail load-out system to establish the allowable train arrival time.

Table 3.12: Rail Load-out Capacity Calculation

No.	Description	Value	Unit	Notes
A	Wagons per train	100	Quantity	
B	Wagon Payload	84.5	Tonnes	
C	Train Capacity	8 450	Tonnes	A x B
D	Export	2.3	Mtpa	272 trains/annum
E	Middlings	1.2	Mtpa	142 trains/annum
F	Briquettes (3 x Trains per Month)	0.3	Mtpa	36 trains/annum
G	Total Production	3.8	Mtpa	450 trains/annum
H	TFR Train Cancellations	45	Trains/annum	From data
I	Mine Train Cancellations	7	Trains/annum	From data
J	Average Pre-loading Delays	00:57	hh:mm	From data
K	Average Loading Time (Export and Middlings)	03:07	hh:mm	From data
L	Average Loading Time (Briquettes)	03:41	hh:mm	From data
M	Average Post-loading delays	00:16	hh:mm	From data
N	Average Train Handling Time (Export and Middlings)	04:20	hh:mm	J + K + M
O	Average Train Handling Time (Briquettes)	04:54	hh:mm	J + L + M
P	System Purge Time Between Products	02:00	hh:mm	Discussion with Operations = 1 hour max.
Q	Max. Product Switchovers	178	Times/annum	E + F
R	Time lost due to purging between product switch	356	hours	P x Q
S	Total Time per Year	8 760	hours	
T	TFR Shut	240	hours	10 days
U	Public Holidays	312	hours	13 days
V	Scheduled Maintenance	508	hours	9 hours/week and 3 hours/month
W	Unscheduled Maintenance	320	hours	96% Reliability
X	Waiting for Stock	0	hours	
Y	Total Time Available	7 024	hours	S - R - T - U - V - W - X
Z	Total number of trains to factor in a year	502	Trains/annum	G + H + I
A1	Required number of trains per day	1.7	Trains/day	Z ÷ (Y ÷ 24)
A2	Required time between trains	14	hours	24 ÷ A1

The train schedule was driven by dynamic week-to-week interaction between the mine's marketing teams and TFR, and it was directly associated with the achievable production targets. The following was established from the calculation:

- Total available time per year to load-out trains = 7 024 hours;
- Number of trains required to be loaded per day = 1.7 trains;
- Required maximum time between trains = 14 hours;
- Minimum time required between two subsequent trains arriving (same product) = ± 5 hours; and
- Minimum time required between two subsequent trains arriving (different products) = ± 7 hours.

Coal Mine A took an average of 4 hours and 40 minutes (Figure 3.22) to handle trains and an average of 3 hours and 41 (Figure 3.23) minutes to load trains, which resulted in a total time of 8 hours and 21 minutes for both handling and loading of trains. Coal Mine A, therefore, historically performed well within the required 14 hours maximum allowable train arrival times.

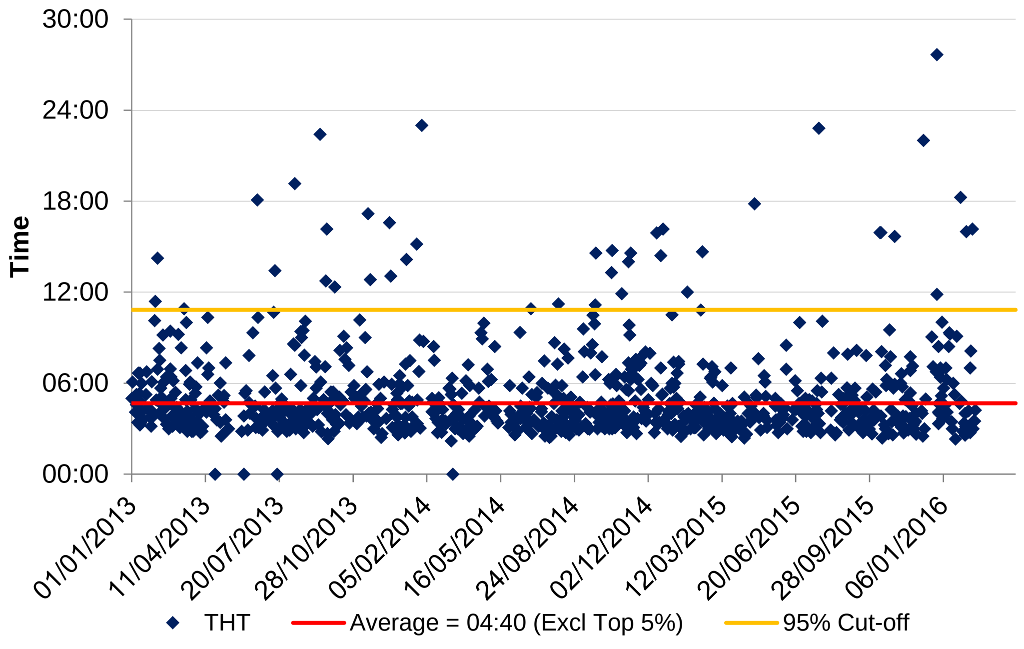


Figure 3.22: Train Handling Time (THT) History

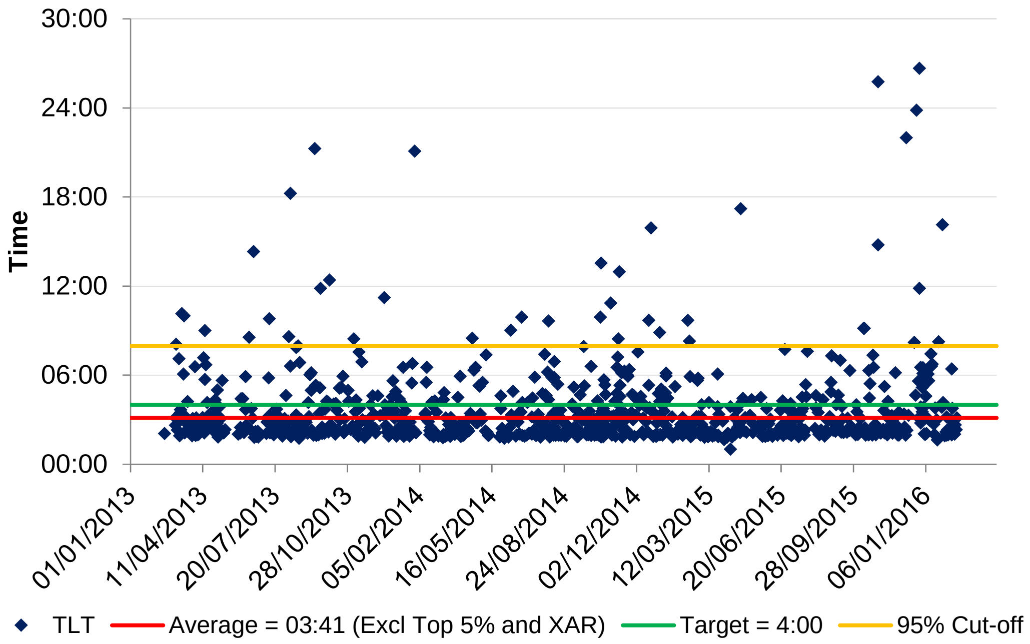


Figure 3.23: Train Loading Time (TLT) History

3.10.2 Product Stockpile Management

The static calculation, as described in Section 3.10.1, was completed with the assumption that product would always be available for conveyance to the rail load-out station. An assessment of the product stockpile capacities was conducted and is summarised in Table 3.13.

Table 3.13: Coal Mine A Stockpile Capacities in Kilo Tonnes (Kt)

Description	Export Product (Kt)	Middlings Product (Kt)	Total (Kt)
Live Capacity	10	10	20
Full Capacity	40	40	80
Emergency Capacity	200	200	400
Theoretical Emergency Capacity Limit			1 350

In the event that the design stockpile capacity was exceeded, coal was pushed out to areas outside the design footprint to prevent potential production stoppages. Coal Mine A did not have a designated emergency stockpile area, but had ample space adjacent to the existing stockpiles for emergency purposes. These areas are defined as contaminated areas. Since production commenced at the mine, there were periods when coal was pushed out, and the emergency capacity exceeded 400 Kt. There was potential to store more than 500 Kt of product within the currently available space. However, there were safety risks and operating cost implications associated with this. The assumption to exclude stockpile movements from the rail load-out capacity analysis was therefore justified.

3.11 Chapter Conclusions

The dynamic simulation required a team of discipline-specific experts and an experienced mining M&S consultant. The project team consulted with the mine operations team during the development of the simulation, which was also vetted by a review team. Both the approach and results of the dynamic simulation were deemed acceptable by the full team. Gensym G2 can be used for the simulation of a mine materials handling value chain. The simulation for Coal Mine A LOM extension project consisted of four integrated models: the Mining Model, BMH G2 Simulation Model, DMS "Black Box" Model, and the Product Handling "Black Box" Model. Modelling time was reduced using "Black Box" models to represent complex system components. The simulation cost was very minimal (less than 1%) in comparison to the capital investment required for the project. Assumptions were made on production rates, in-flight material and PSD.

A variable feed rate from the mine was generated in Palisade's @RISK software and incorporated into Gensym G2. Planned stoppage events were programmed into Gensym G2 model components. Historical data was used to generate probability distribution functions in Gensym G2 to simulate unplanned stoppage events (equipment breakdowns). The incorporation of TOC principles into a mine plan was essential and can mitigate the risk of not achieving mine design targets during production. Palisade's @RISK software was used to this effect to determine mining activity buffer capacities. Black, green, yellow and red buffer capacities were calculated for each of the different mining activities. These buffer capacities (in linear metres) specified the level of management intervention to ensure that no interference occurs between activities and that planned production is achieved.

The Palisade's @RISK software simulation to determine the annual achievable tonnage from the mine considered the number of days the BMH system was available. The mining DOT was calculated as 59%, and the mining COT at 66%. The COT calculation is based on the use of the CAT 994 FEL as a spare machine during periods when an excavator was not available due to required maintenance. The simulation was used to develop a variable mining input file which was used in the Gensym G2 simulation to calculate the achievable production from the mine. The result of the simulation was that the mine can produce 19 684 t, at a 95% confidence level, if in-pit inventory per mining activity is maintained. The BMH DOT was calculated to be 64%. A "normal" PDF was used to simulate the MTTF and a "triangular" PDF was used to simulate the MTTR of the various pieces of equipment in the BMH system. These PDFs were derived using historical downtime equipment data. The BMH feed rate used in the model is the maximum feed rate of 1 263 t/h obtained from the mechanical design basis. Regarding the DMS Plant, the DOT is calculated at 76%. A "Weibull" PDF, derived from historical data, was used to simulate the MTTF and MTTR of the DMS Plant. The DMS Plant feed rate is based on a capacity analysis, and two scenarios were run in the model, which were nominal (861 t/h) and peak (968 t/h). A performance test on the Reclaimer revealed that the maximum capacity was 948 t/h and this is regarded as adequate to achieve annual production targets.

Scenarios involving the incorporation of a Buffer Silo between the Primary Receiving Conveyor and the Overland Conveyor of varying capacity (0 t to 6 000 t) reveal that the system with no Silo results in 5.93 Mtpa. A 2 000 t Silo provided the highest system production of 5.97 Mtpa. The additional capital of ± R44 million to construct a 3 000 t Silo was not justifiable, even though the inclusion of the 3 000 t Silo resulted in the maintenance of a higher average Raw Coal Stockpile level. The assessment of the system design capacity revealed that annual targets can be achieved and that no design changes are required to be implemented. The G2 model was found to be stable and consistent during a variability test in which variability was found to be less than 1%. The rail load-out station had sufficient capacity to accommodate the three export coal products. The required maximum time between trains to sustain the 6.484 Mtpa production target was 14 hours, and the operation performed well within this requirement, requiring a time of 8 hours 20 minutes between trains. The next chapter describes the validation work conducted.

4. VALIDATION

4.1 Introduction

The work conducted to validate the simulation is described in this chapter. Data was acquired from the mine over a four-month period from June 2018 to September 2018. The sources of data include the mine survey department, the Minfo system, the BMH and DMS Plant downtime database, and the Supervisory Control and Data Acquisition (SCADA) system. The Minfo system is the repository for mining equipment and production data. All BMH system and DMS Plant instrumentation data, for example, conveyor belt scale readings, are stored in the SCADA system database. Many discussions were held with mine personnel to ensure that the data received was understood and interpreted correctly.

In the mining discipline, the buffer management history (aerial photography) of the different mining activities are analysed and compared to the mine design activity buffer length requirements. The average DOT and COT for the validation period for the Hitachi EX3600 Excavators were calculated from production data and compared to the simulation input. The average DOT for the Komatsu 730e Trucks was calculated in a similar manner. The DOT per truck per day, including the best uptime achieved in a specific day, was calculated and compared to the previous calculations and simulation input. The analysis of the mine itself ended with a comparison of the actual vs. planned average and peak feed rate to the ROM Tip and the production from the mine per day.

In the BMH discipline, the DOT was calculated from downtime records and compared to the previous DOT calculation. During the month of September 2018, which was the best production month, the production (t) per day was calculated. The actual vs. planned average and peak production of the BMH system was calculated and compared to the simulation input. A comparison was also conducted for the actual vs. planned DOT for the DMS Plant. During the validation period, the monthly production of the DMS Plant was calculated, including the production (t) per day for September 2018. The actual peak and nominal production rates were calculated and compared to the design basis. The validation was concluded with a calculation of the best combination of performance of the sub-systems of the materials handling value chain and comparison with the simulation output.

4.2 Mining – Simulation Input Comparison

4.2.1 TOC Buffer Management

Data Collection

The mine survey department conducted regular aerial surveys such that the buffer lengths for each of the different mining activities can be recorded. The mining block layout and buffer lengths per activity were superimposed onto aerial photographs and circulated to the mine operational management team. Figure 4.1, Figure 4.2 and Figure 4.3 represent the typical information that was distributed. Figure 4.1 is the overall pit layout, and Figure 4.2 and Figure 4.3 represent the two different portions of the pit.

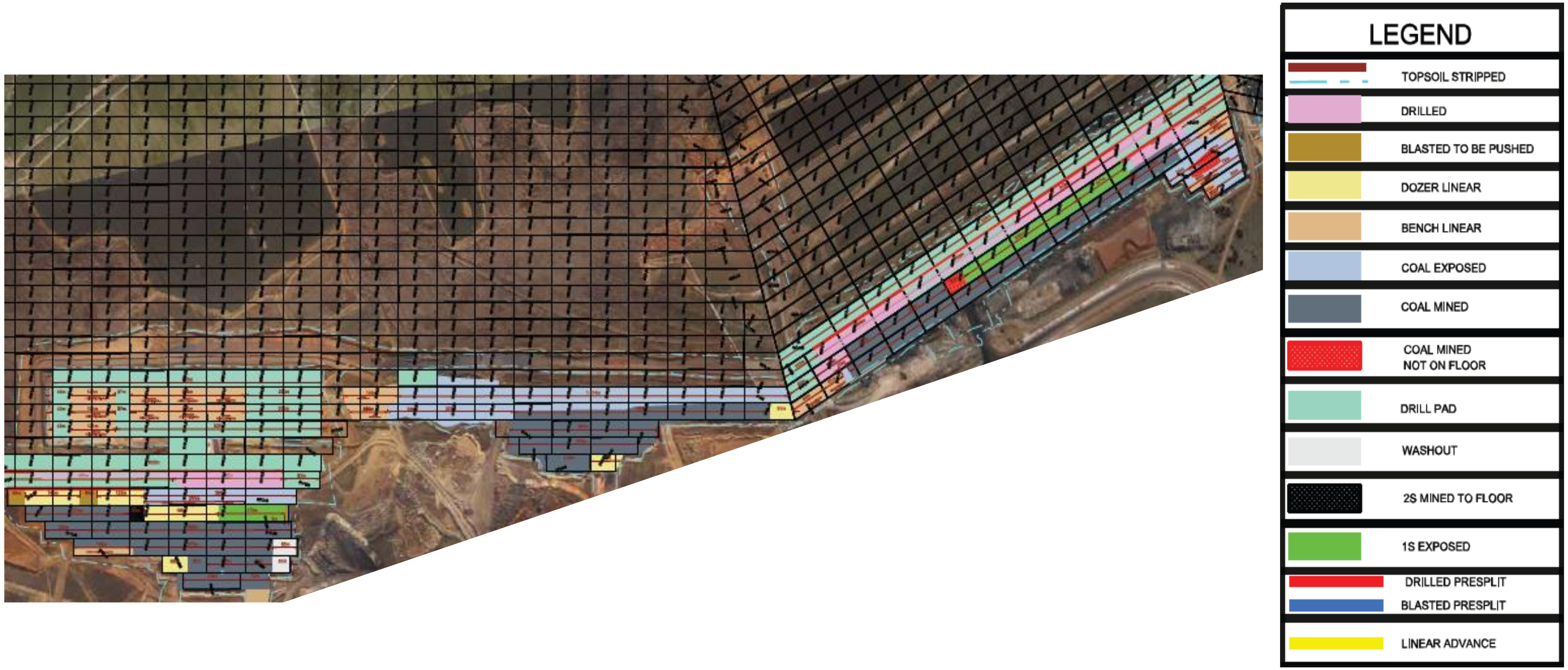


Figure 4.1: Overall Pit Layout with Mining Activity Buffer Lengths

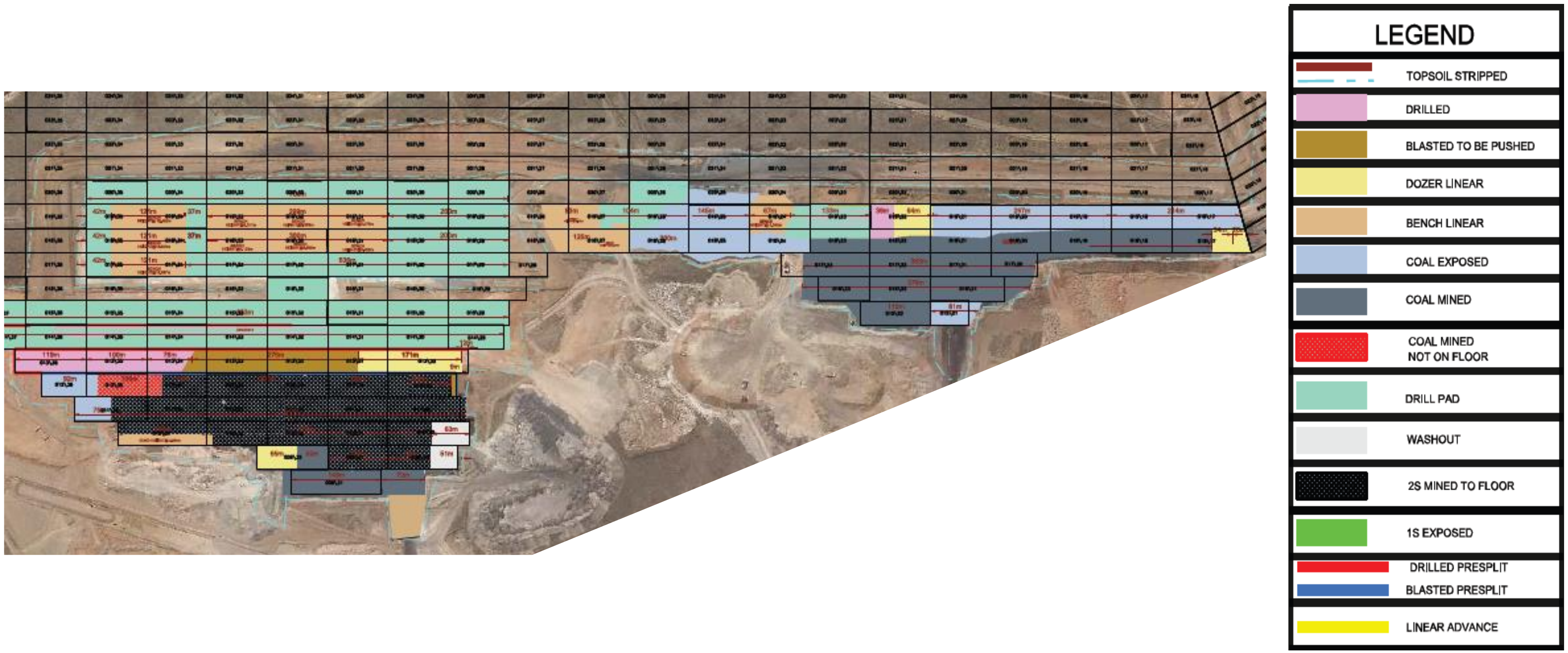


Figure 4.2: Pit 1 Layout with Mining Activity Buffer Lengths

Figure 4.3: Pit 2 Layout with Mining Activity Buffer Lengths

The definitions of each buffer type are given below:

- Drill Pad: Area which has been stripped of topsoil and is available for drilling;
- Drilled: Area in which drilling has been completed and is now ready for blasting;
- Blasted to be Pushed: This refers to an area in which overburden is required to be dozed;
- Dozer Linear: This is an area which has overburden which is being dozed;
- Bench Linear: This refers to the area which contains overburden which cannot be dozed and can only be moved using trucks and shovels;
- Coal Exposed: These are areas where coal has been exposed and is in the process of being drilled; and
- Coal Mined Not on Floor: This refers to an area where coal has been mined, but there is still coal remaining or lying on the floor. In other words, the coal has not been taken out completely.

The buffer definitions from the LOM extension project feasibility phase (Table 3.2) were compared to the definitions in the mine survey department TOC reports. There was a need to obtain alignment between the two definitions. Table 3.2 represents a scenario in which the 4 Seam was present and mined above the 2 and 1 Seams. During the period June 2018 to September 2018, while the validation work was conducted, there was no 4 Seam present in the pit and, therefore, no inter-burden between the 4 Seam and the 2 and 1 Seams. There was also no need to conduct pre-split drilling and blasting to mine the 2 and the 1 Seams as the pre-split drilling and blasting were conducted by the project team. The 2 Seam and the 1 Seam were mined as a single entity together with the parting between the two coal seams. Therefore, there was also a need to adapt the information in Table 3.2 to suit the geology, pit layout and mining methods applied at the time when the validation was conducted. This exercise is shown in Table 4.1.

Table 4.1: Project Feasibility Phase Buffer Definition (Adaptation from Table 3.2) vs. Mine Survey Department Buffer Definition

Material Horizons	Activity (Feasibility Phase Definition)	Activity (Mine Definition)	Red Buffer (m)	Yellow Buffer (m)	Green Buffer (m)
Softs	Pre-strip - Truck and Shovel	Drill Pad	1 280	2 500	4 000
Hard Burden	Drilling - Expose No. 2 and 1 Seam	Drilled	500	750	1 800
Hard Burden	Blasting - Expose No. 2 and 1 Seam	Blasted to be Pushed	500	750	1 440
Hard Burden	Dozing - Expose No. 2 and 1 Seam	Dozer Linear	180	300	1 440
Hard Burden	Truck and Shovel - Expose No. 2 and 1 Seam	Bench Linear	255	450	1 080
No. 2 and 1 Seam	Coal Drilling	Coal Exposed	500	850	1 440
No. 2 and 1 Seam	Truck and Shovel	Coal Mined Not on Floor	405	750	1 080

Each aerial photo (170 in total) circulated during the validation period (1 June 2018 to 30 September 2018) was analysed. Buffer lengths were measured off the aerial photos and recorded in MS Excel. The recorded lengths were compared to the information in the Minfo system. There were information gaps in Minfo, and some of the lengths measured off the drawings did not correlate with the lengths recorded in Minfo. For this reason, it was decided to base the validation on information from the aerial photography.

Data Analysis

The actual buffer lengths were compared to the recommended red, yellow and green buffer lengths in Table 4.1. In Figure 4.4 to Figure 4.10, the horizontal lines represent the red, yellow and green buffers. The blue line represents the actual buffer. Figure 4.4 shows the Drill Pad Buffer analysis.

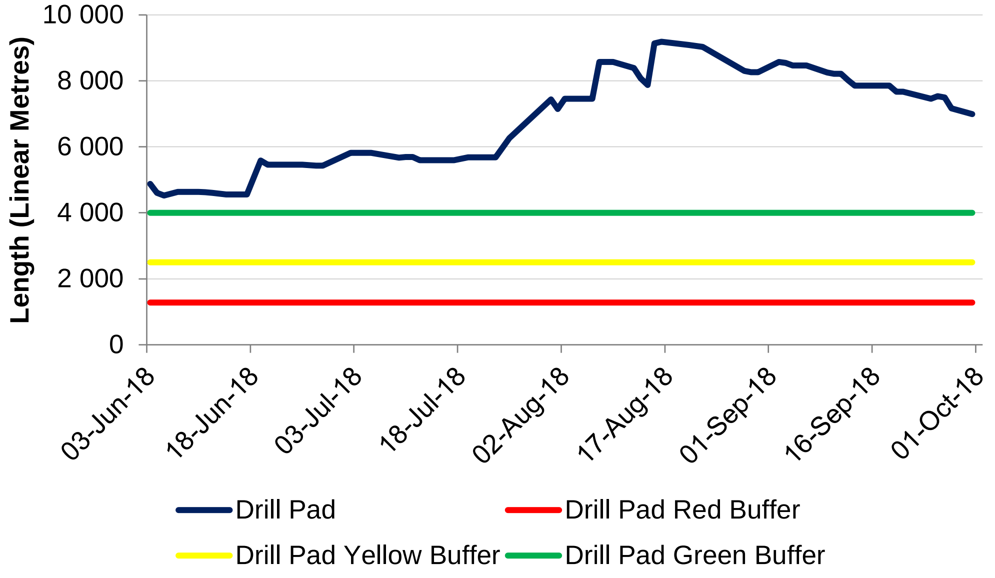


Figure 4.4: Drill Pad Buffer Analysis

The drilling pad buffer operated above the green buffer and was, therefore, sufficient for the validation period. The drilling of the hard burden activity buffer analysis is shown in Figure 4.5.

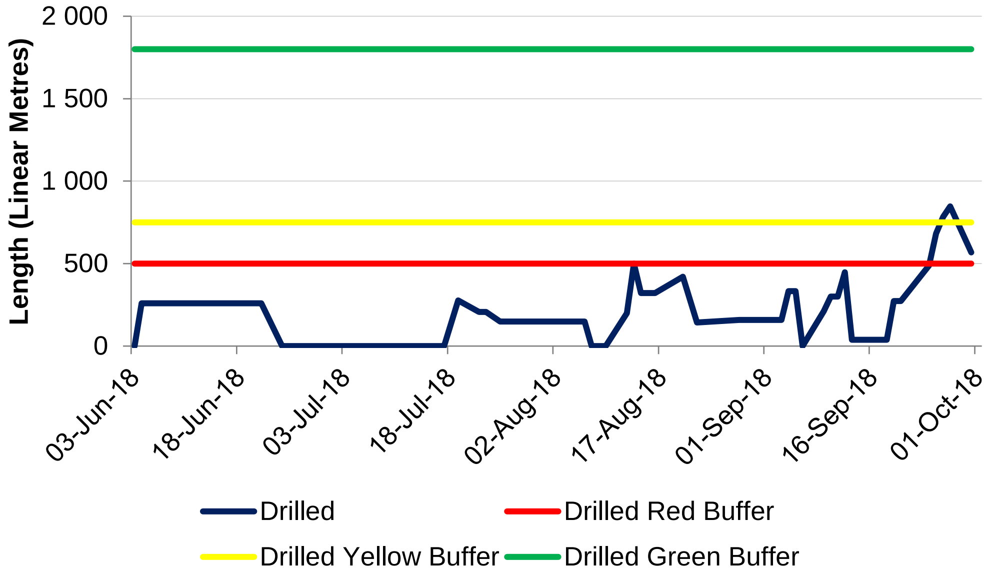


Figure 4.5: Drilled Buffer Analysis

The drilling activity buffer was predominantly below the red level. In the last week of September 2018, the buffer showed signs of improvement and rose above the yellow level, but then dropped again to the red level. Figure 4.6 shows the blasted (hard burden) to be pushed activity buffer analysis.

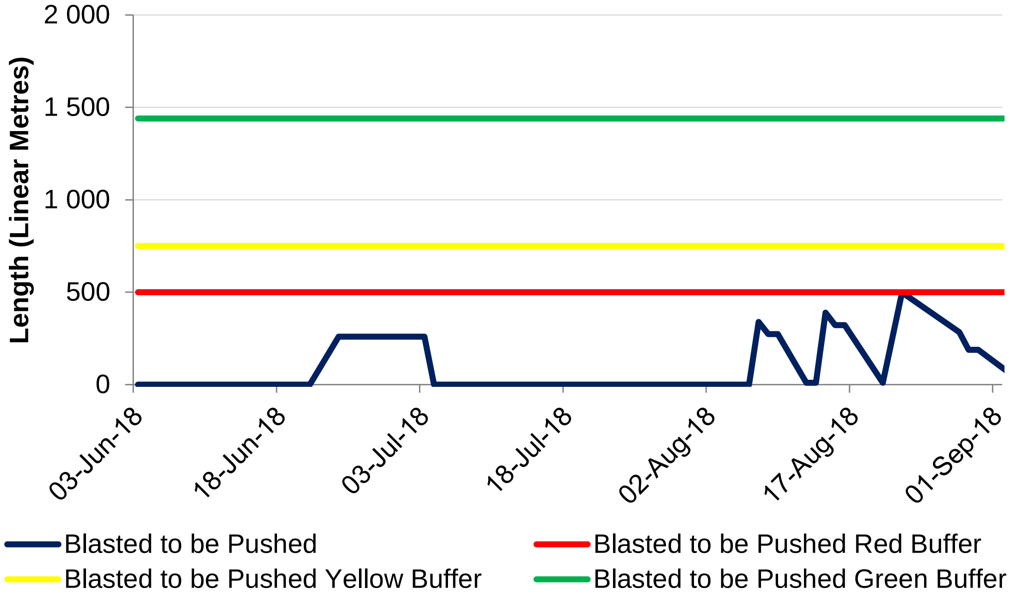


Figure 4.6: Blasted to be Pushed Buffer Analysis

The blasted (hard burden) to be pushed activity buffer operated on 0 m for the majority of the time. When the buffer was above the 0 m level, it was still below the red buffer level. The insufficient buffer had an impact on the buffer for the dozing activity, as can be seen in Figure 4.7.

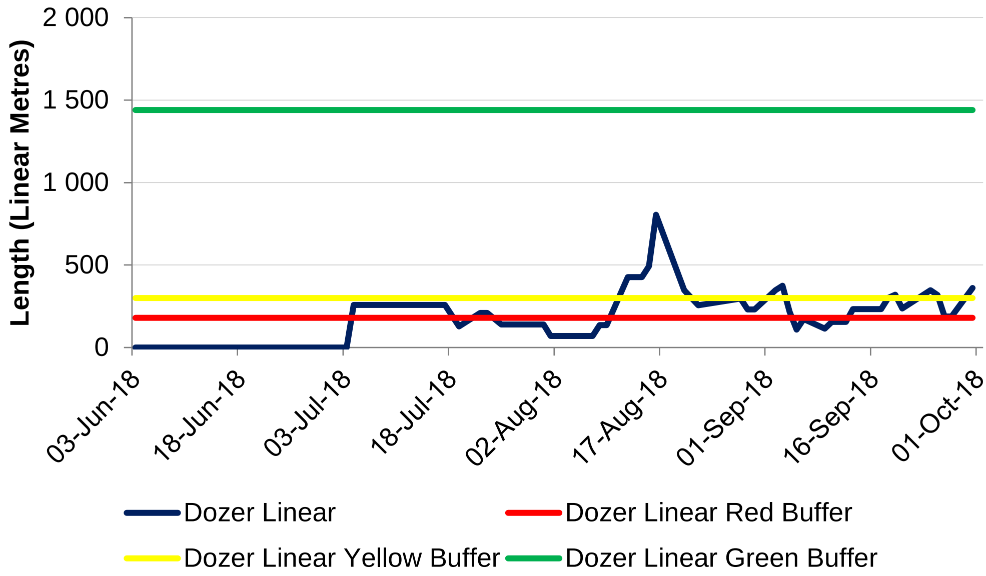


Figure 4.7: Dozer Linear Buffer Analysis

For the month of June 2018, no Dozer Linear buffer existed. The buffer level then picked up and operated predominantly below the yellow buffer level. There was a period of only ± 10 days in which the buffer was between the yellow and the green zones. The bench liner (truck and shovel of hard burden) activity buffer analysis is shown in Figure 4.8.

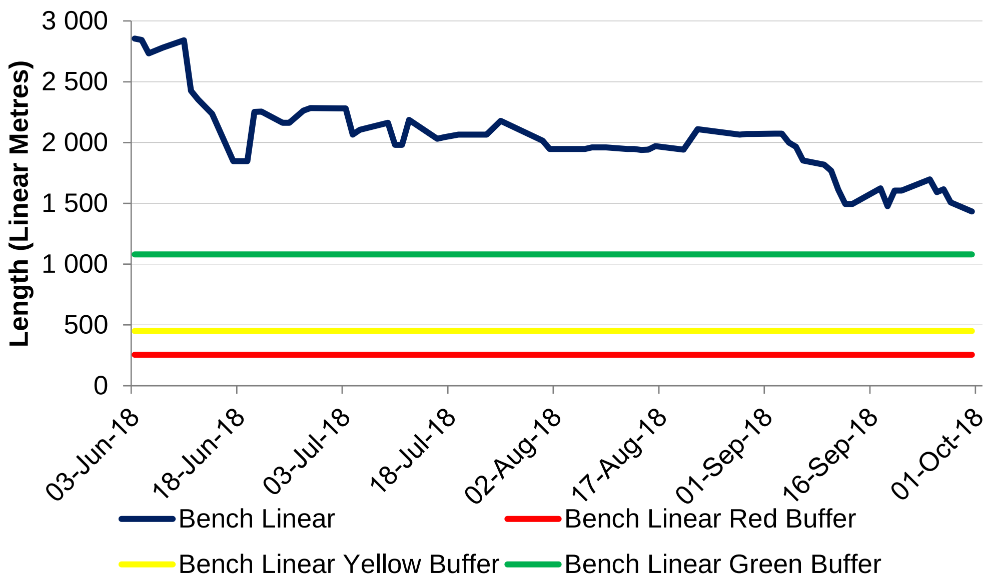


Figure 4.8: Bench Linear Buffer Analysis

The bench linear (truck and shovel of hard burden) activity buffer was sufficient for the duration of the validation period. Figure 4.9 shows that there was a sufficient amount of coal exposed for the validation period.

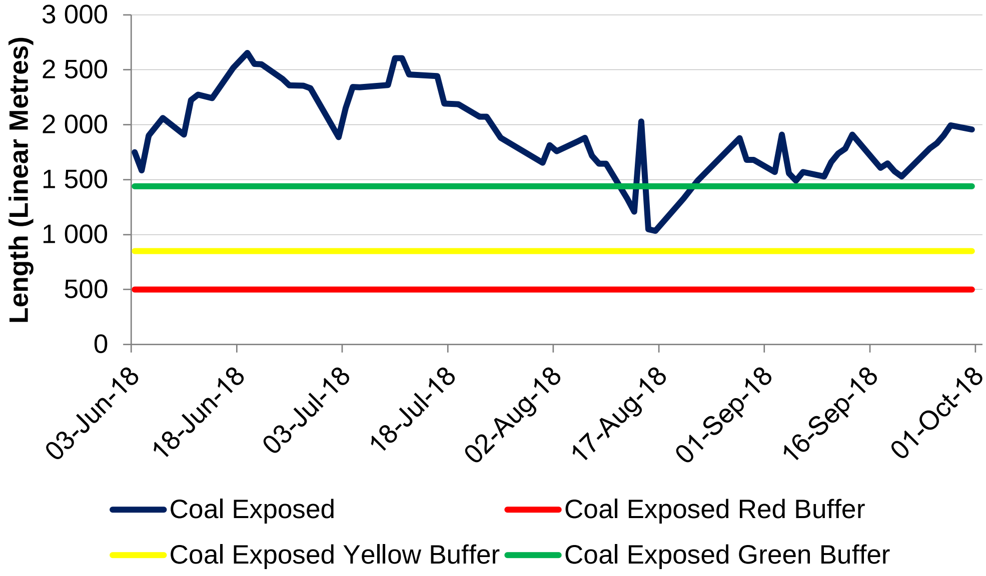


Figure 4.9: Coal Exposed Buffer Analysis

The mine could have achieved an adequate coal exposed buffer by assigning the truck and shovel fleet to move the hard burden which was originally intended to be blasted and dozed. The hard burden could have been soft enough not to require drilling and blasting. The coal mined not on floor or the truck and shovel of coal activity buffer (Figure 4.10) was insufficient.

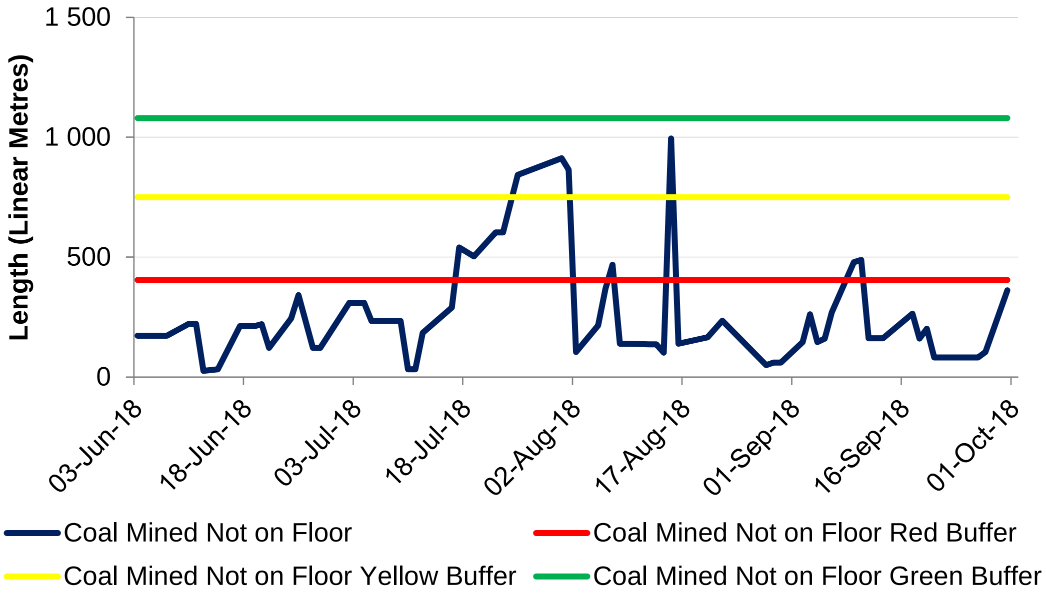


Figure 4.10: Coal Mined Not on Floor Buffer Analysis

The buffer of coal to be mined was insufficient for the majority of the time (± 14 weeks), apart from a period of ± 2 weeks when the buffer operated between the green and yellow zones. The reason for this could be that the truck and shovel capacity meant for coaling was assigned to the truck and shovel activity for hard burden, instead of using drilling and blasting and then dozing. Another reason could be poor coal drilling performance, which impacted the buffer available for the truck and shovel of coal. The buffer for the truck and shovel activity of coal was insufficient for ± 14 weeks.

4.2.2 Coaling Operating Time (Hitachi EX3600 Excavator)

Data Collection

Data gathering for the mining operation was conducted by the Mine Control Room Operator (MCRO). This was done at the start of the shift, during the shift, and at the end of the shift. The MCRO was responsible for uploading information into the Minfo system. At the start of the shift, the status of each piece of Heavy Mobile Equipment (HME) was confirmed. The status could be breakdown, scheduled maintenance, or available for mining. The MCRO and the Engineering Planner communicate with each other during the shift with regard to the status of equipment which is either scheduled for maintenance or undergoing repair work because of a breakdown event. The MCRO also keeps in regular contact with the HME operators and records operational delays and breakdown events. At the end of the shift, the MCRO is provided with a shift report which contains all the production data for the shift. The MCRO validates the information captured in Minfo during the shift. The previous day's data is further validated during morning meetings between the Mining, Engineering and Plant departments when the data is discussed, corrections made if required, and signed-off. The MCRO updates the Minfo system if required.

The raw data used to compile Figure 3.13 was analysed, and downtime codes per category were noted. The downtime codes in the new data set were then allocated to the different categories in a similar fashion as conducted previously. The sum totals for the different categories were then computed per excavator, using an MS Excel Pivot table. An average of the hours for the two excavators was calculated which led to the compilation of Figure 4.11. The MCRO was also tasked with recording the time spent by each of the excavators and FEL on the coaling-related activity. The time that the CAT 994 FEL was used for coaling is shown in Figure 4.11.

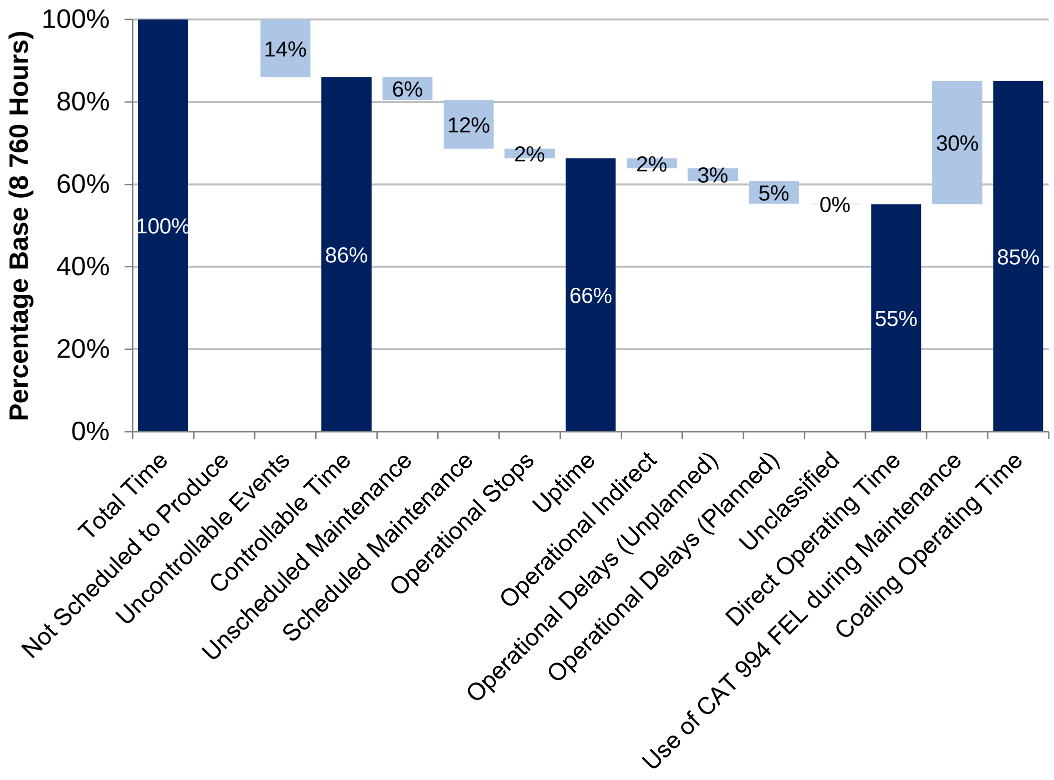


Figure 4.11: Mining Time Model (Hitachi EX3600 Excavators) from June 2018 to September 2018

Controllable Time, Uptime and DOT were calculated at 86%, 66% and 55% respectively. COT was calculated at 85%, as a result of CAT 994 FEL usage which contributed to an overall improvement in excavator availability.

Data Analysis

The analysis conducted (refer to Table 4.2) took the form of a comparison between Figure 3.13 (current) and Figure 4.11 (previous).

Table 4.2: Mining COT Comparison (Actual vs. Planned)

No.	Description	Percentage of 8 760 Hours (Actual)	Percentage of 8 760 Hours (Planned)
A	Total Time	100%	100%
B	Not Scheduled to Produce	0%	4%
C	Uncontrollable Events	14%	6%
D	Controllable Time	86%	90%
E	Unscheduled Maintenance	6%	7%
F	Scheduled Maintenance	12%	9%
G	Operational Stops	2%	3%
H	Uptime	66%	72%
I	Operational Indirect	2%	2%
J	Operational Delays (Unplanned)	3%	3%
K	Operational Delays (Planned)	5%	4%
L	Unclassified	0%	3%
M	DOT	55%	59%
N	Use of 994 During Maintenance	30%	7%
O	COT	85%	66%

There was no downtime booked to "Not Scheduled to Produce", although there were three public holidays during the validation period, Youth Day (16 June), National Women's Day (9 August), and Heritage Day (24 September). Uncontrollable Events (14%) was more than double the previous allowance (6%). Controllable Time (86%) was calculated to be 4% lower than previous. Unscheduled Maintenance, Scheduled Maintenance, and Operational Stops were between 1% and 3% of the previous allowance. Uptime was calculated to be 6% lower than the previous allowance. Operational Indirect and Operational Delays (Unplanned) were the same as previous estimates. However, Operational Delays (Planned) was 1% higher than previous. No downtime was booked to Unclassified, while the previous estimate was 3%. DOT was calculated to be 4% lower than the previous calculation. The CAT 994 FEL was used 23% of the time more than estimated previously. This resulted in the COT being 19% higher than the previous estimate as a result of the unplanned usage of the CAT 994 FEL.

4.2.3 Coaling Operating Time (Komatsu 730e Trucks)

Data Collection

Downtime data for the five Komatsu 730e Trucks from the mine's Minfo system was analysed. The average downtime hours for all the trucks were calculated per downtime category (Figure 4.12).

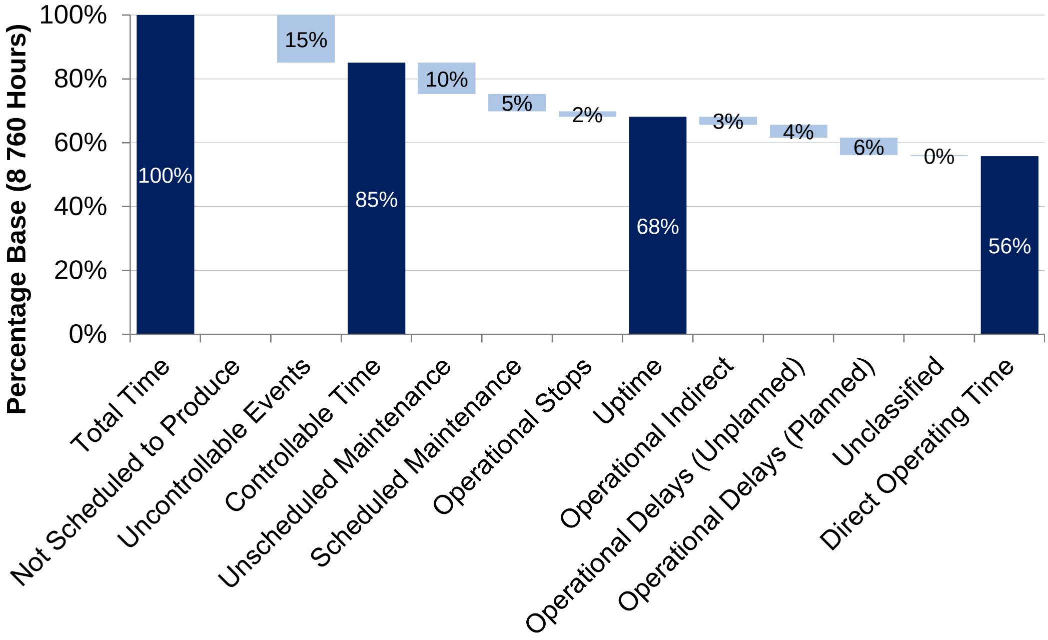


Figure 4.12: Mining Time Model (Komatsu 730e Trucks) from June 2018 to September 2018

The average DOT was calculated and found to be 56%. The DOT hours that the five trucks (ODT001 to ODT005) achieved per day from June 2018 to September 2018 is plotted in Figure 4.13.

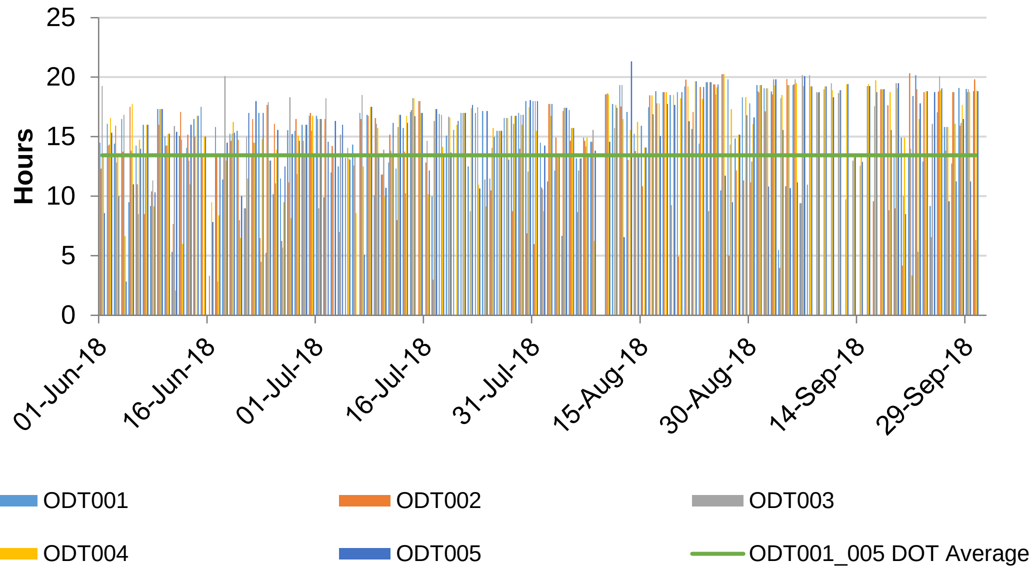


Figure 4.13: Komatsu 730e Trucks DOT (Hours) Per Day from June 2018 to September 2018

The average DOT achieved was 13 hours. The best uptime the trucks achieved and the average is shown in Table 4.3.

Table 4.3: Komatsu 730e Truck Hours Achieved Per Day from June 2018 to September 2018 (Top 10 Performance)

Truck No.	Date	DOT (Hours) Achieved
ODT001	22-Sep-18	20.16
ODT002	26-Aug-18	20.24
ODT002	21-Sep-18	20.34
ODT003	18-Jun-18	20.09
ODT003	26-Aug-18	20.24
ODT003	06-Sep-18	20.16
ODT003	07-Sep-18	20.16
ODT003	25-Sep-18	20.06
ODT004	26-Aug-18	20.24
ODT005	13-Aug-18	21.32
Average		**20.30**

The average of the top 10 DOT the trucks achieved for the validation period was calculated to be 20.3 hours.

Data Analysis

The average DOT achieved by the trucks for the validation period was 56%, which equated to an average DOT of 13 hours per day. The average of the top 10 best uptime the trucks achieved (20.3 hours) was within 0.5% of the calculation conducted in the LOM extension project feasibility phase (20.4 hours) which was a required input parameter for the simulation.

4.2.4 Feed Rate to the ROM Tip

Data Collection

Information in the Minfo database indicates the time each truck spent on coaling and overburden related activities. The total DOT and the total coaling time for the trucks were compared (Figure 4.14).

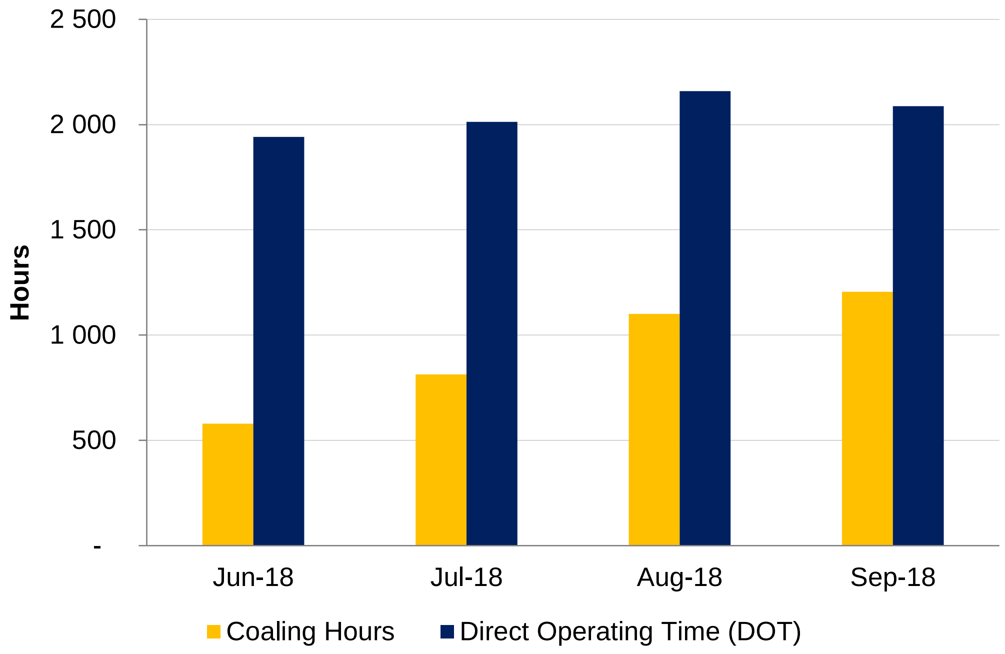


Figure 4.14: Komatsu 730e Trucks DOT and Coaling Hours Per Month

The total DOT for the trucks was 8 200 hours and the total coaling time for the trucks was 3 701 hours. The trucks were used, on average, 45% of the

DOT for coaling-related activities. Dedicated overburden and coaling fleets were not used as proposed during the project feasibility study. Excavators and trucks were used interchangeably between overburden- and coaling-related activities. The total DOT and the coal loading time for the excavators and FEL were compared (Figure 4.15).

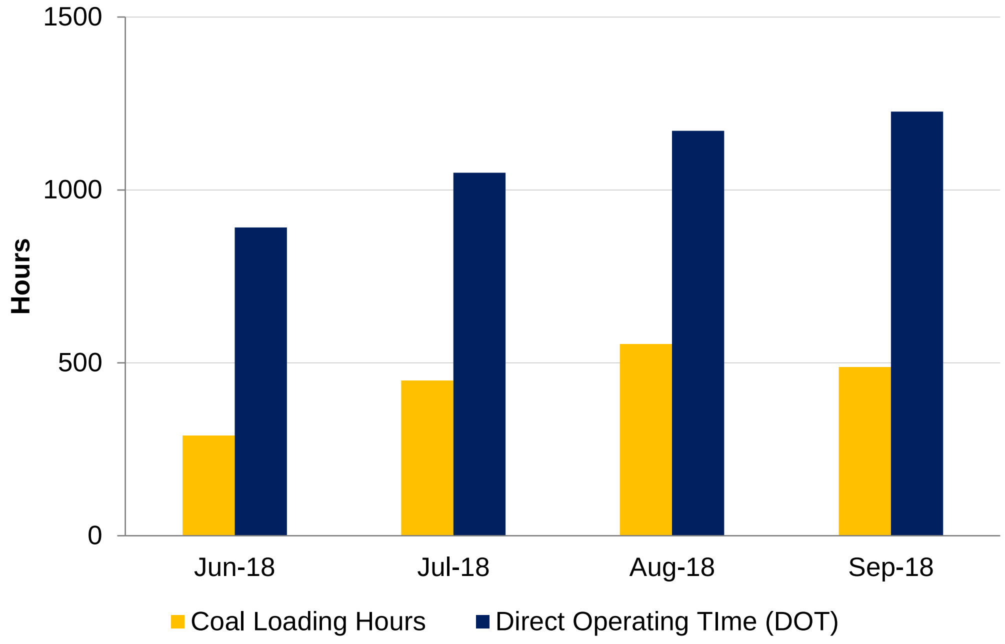


Figure 4.15: Hitachi EX3600 Excavators and CAT 994 FEL DOT and Coal Loading Hours Per Month

The total DOT was 4 338 hours and the total coal loading time was 1 787 hours (42% of DOT). Figure 4.16 shows the number of loaders used on coaling activities and the average production (t/h) achieved.

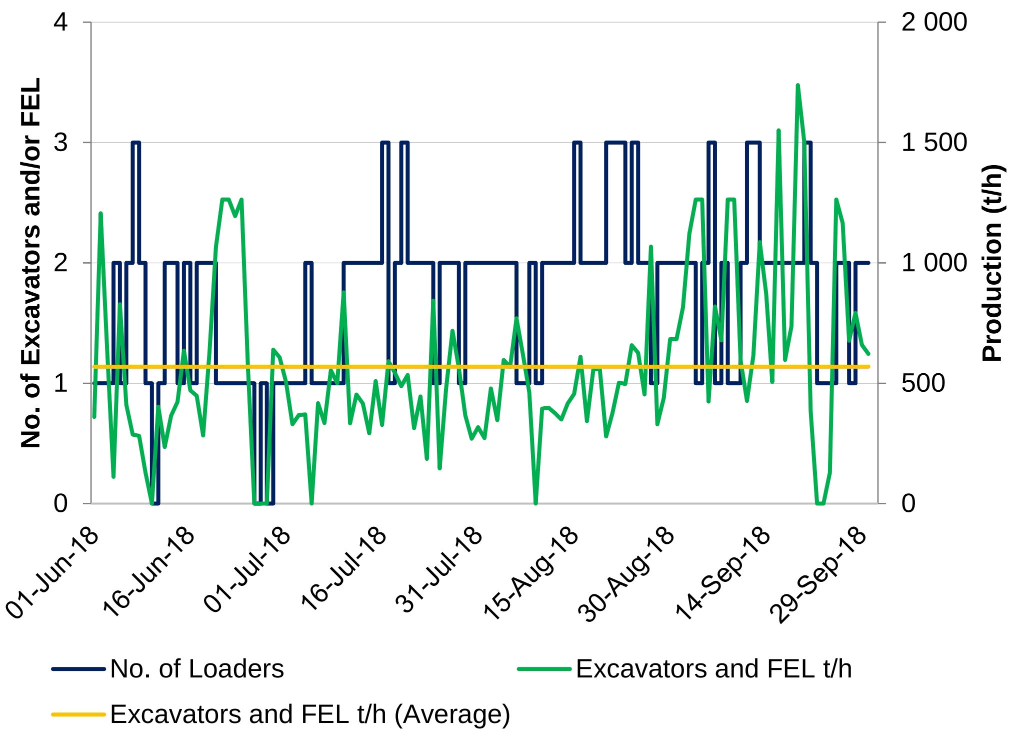


Figure 4.16: Number of Loaders and/or FEL vs. Mine Production

The average production achieved was 569 t/h. The mine was designed to use a single excavator or loader on coal. The data in Figure 4.16 confirms that there was a deviation from the mine plan. The following results are the peak production achieved per excavator or loader combination:

- One excavator and/or FEL = 1 263 t/h;
- Two excavators and/or FEL = 1 739 t/h; and
- Two excavators and FEL = 1 502 t/h.

The production information for the mine was obtained from the Minfo system (Figure 4.17).

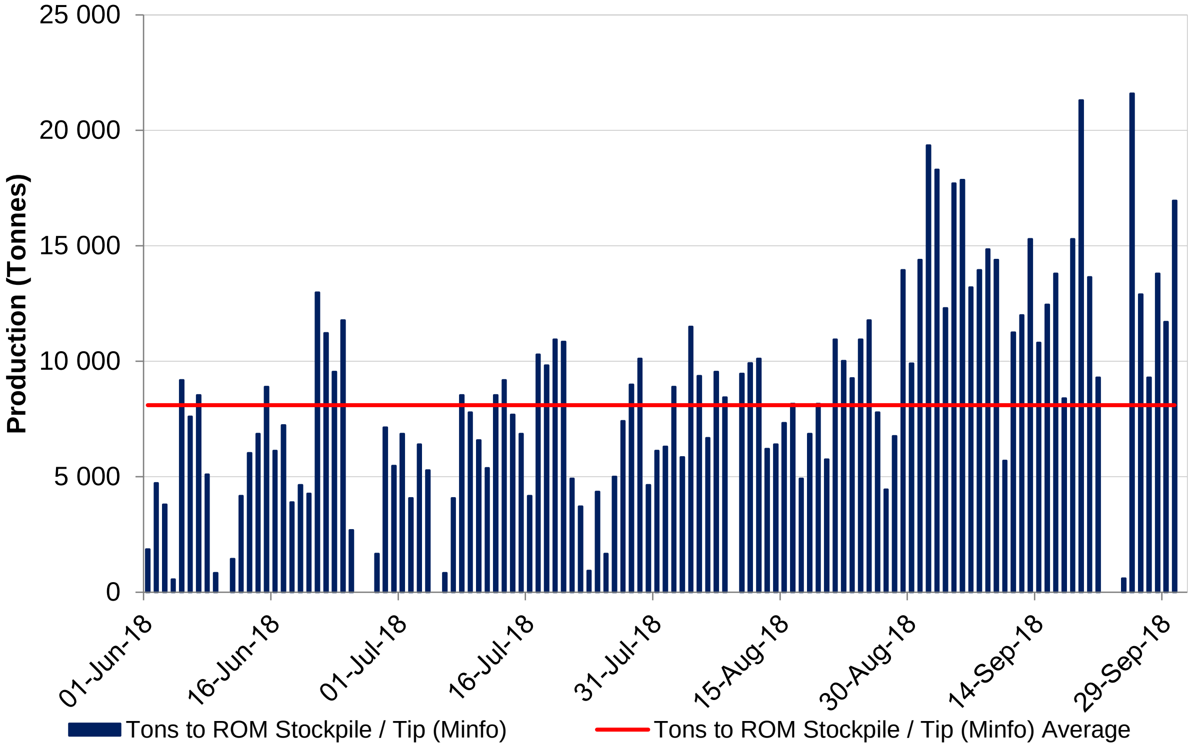


Figure 4.17: Mine Production from June 2018 to September 2018

The average daily production was 8 101 t. The three highest mine production days were 1 September 2018 (19 350 t), 19 September 2018 (21 300 t), and 25 September 2018 (21 600 t). There were instances when the mine did not produce, and these downtime events are collectively described in Section 4.2.2 and Section 4.2.3. The mine performance was below the average monthly target production, as can be seen in Figure 4.18.

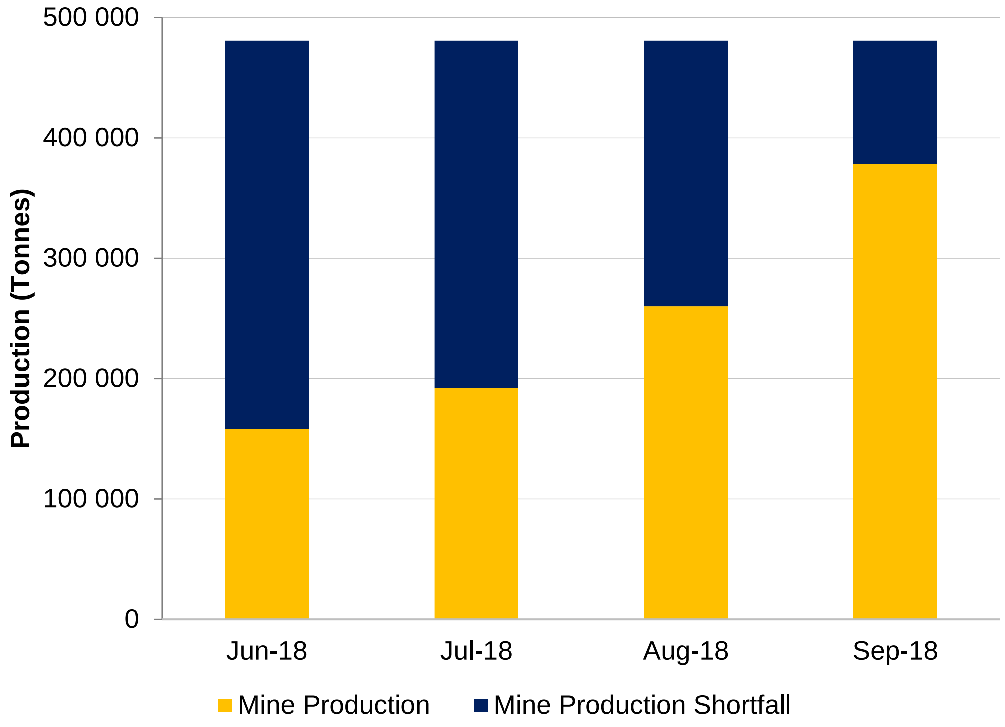


Figure 4.18: Mine Production Performance

Mine production was continuously improved per month from June 2018 to September 2018. There was ± 1 000 000 t produced by the mine, but the shortfall during the validation period, based on the required monthly average production to achieve 5.769 Mtpa, was ± 930 000 t.

Data Analysis

The trucks were used 45% of the time for coaling, and the excavators and/or FEL was used 42% of the time. With reference to Table 4.4, the mine achieved production of 1 263 t/h, and this is in line with the calculation conducted in the LOM extension project feasibility phase.

Table 4.4: Actual vs. Planned Feed Rate to ROM Tip

Actual or Planned	Probability (Risk)	Production (t/d)	Production (t/h)
Actual	Max	21 600	1 263
	P(95)	8 101	569
Planned	Max	23 786	1 263
	P(95)	19 684	937

The highest production achieved was 1 739 t/h, but this was with two excavators, or with one excavator and one FEL. The intent of the mine plan was to use one dedicated excavator, and to use the FEL as a back-up machine, and not in parallel with the excavator. There were times when the mine used both excavators and the FEL, but only achieved production of 1 502 t/h. The use of both excavators and the FEL in parallel on coaling activities was also not intended. The maximum tonnage the mine achieved was 21 600 t, which was 10% greater than the planned tonnage at a P95 confidence level. However, this tonnage was not achieved consistently but there is an indication that this can be achieved.

4.3 BMH – Simulation Input Comparison

4.3.1 DOT

Data Collection

The downtimes from 1 June 2018 to 30 September 2018 recorded by the mine were analysed for this research. The process used by the mine to log downtimes entailed the discussion and agreement of the previous day's downtime hours at daily morning meetings held between the mine, plant and engineering teams. The information was then entered into MS Excel. The downtimes were classified as per the time model definitions used in the project feasibility phase. After each downtime was classified, the sum totals for the different categories were computed using a MS Exel Pivot table. These sum totals were used to develop Figure 4.19.

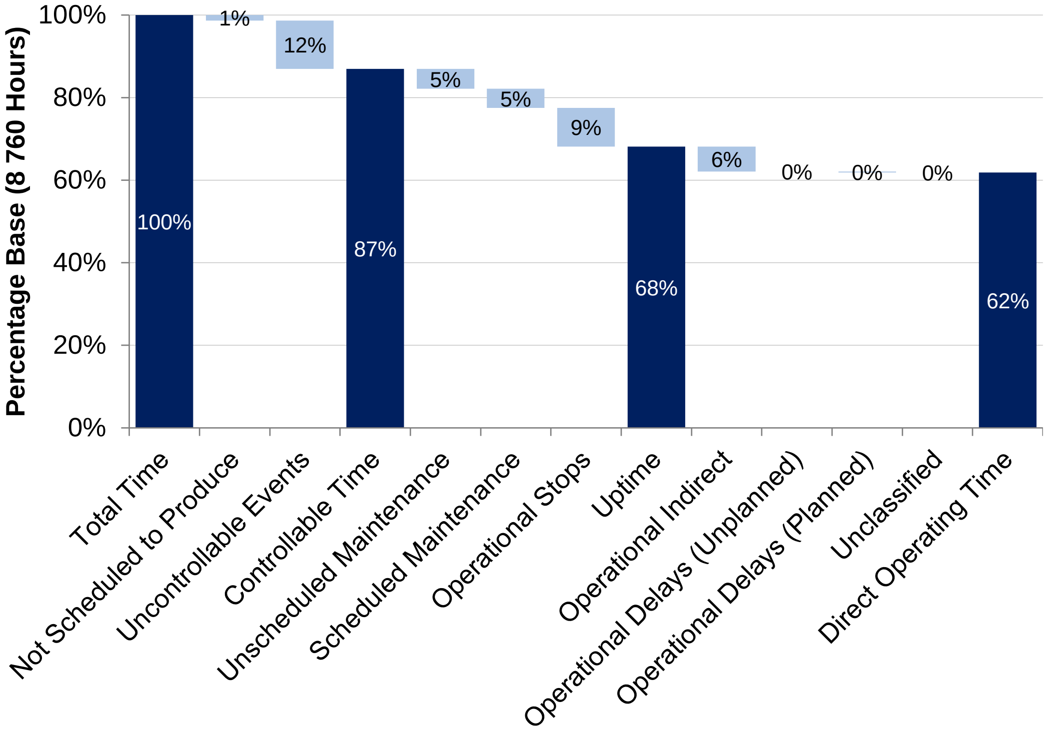


Figure 4.19: BMH Time Model from June 2018 to September 2018

Controllable Time was calculated at 87%, and Uptime at 68%. Considering Operational Indirect, DOT was calculated at 62%.

Data Analysis

The actual BMH DOT (Figure 3.14) was compared to the planned BMH DOT (Figure 4.19) (see Table 4.5).

Table 4.5: BMH DOT Comparison (Actual vs. Planned)

No.	Description	Percentage of 8 760 Hours (Actual)	Percentage of 8 760 Hours (Planned)
A	Total Time	100%	100%
B	Not Scheduled to Produce	1%	4%
C	Uncontrollable Events	12%	5%
D	Controllable Time	87%	91%
E	Unscheduled Maintenance	5%	8%
F	Scheduled Maintenance	5%	7%
G	Operational Stops	9%	1%
H	Uptime	68%	75%
I	Operational Indirect	6%	10%
J	Operational Delays (Unplanned)	0%	0%
K	Operational Delays (Planned)	0%	0%
L	Unclassified	0%	0%
M	DOT	62%	64%

With reference to Table 4.5, the Not Scheduled to Produce calculation was 3% lower than the previous. Uncontrollable Events was 7% higher, which resulted in Controllable Time being 4% lower than the previous calculation. Unscheduled and Scheduled Maintenance were within ± 3% of the previous estimate, but Operational Stops were 8% higher, which resulted in Uptime being 7% lower than the previous estimate. Operational Indirect was 4% lower than the previous value, which resulted in the overall DOT being 2% lower.

4.3.2 Feed Rate to Raw Coal Stockpile

Data Collection

Production tonnages between June 2018 and September 2018 available on the Minfo system were analysed. The Primary Receiving Conveyor and Stacker Feed Conveyor belt scale readings were obtained from the mine SCADA system and compared to the information on the Minfo system (Figure 4.20).

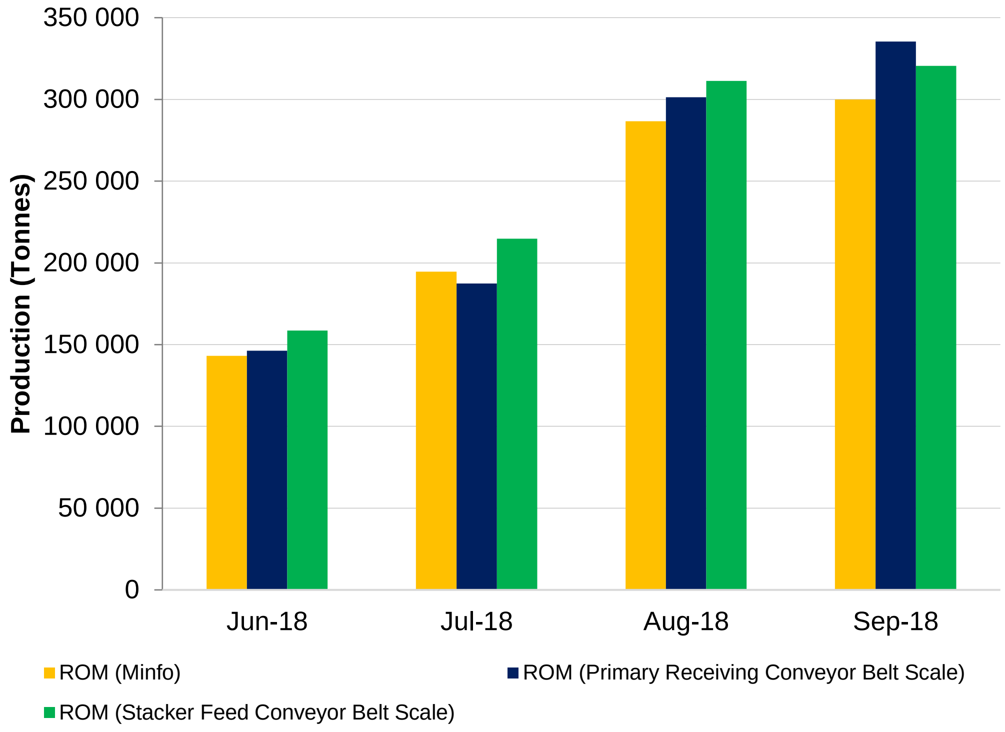


Figure 4.20: ROM Tonnes Comparison (Minfo vs. Conveyor Belt Scales)

There was a 3% average difference between the Minfo information and the Primary Receiving Conveyor Belt Scale. There was a 5% average difference between the Primary Receiving Conveyor Belt Scale and the Stacker Feed Conveyor Belt Scale. Figure 4.21 shows the production calculated using the Primary Receiving Conveyor belt scale readings.

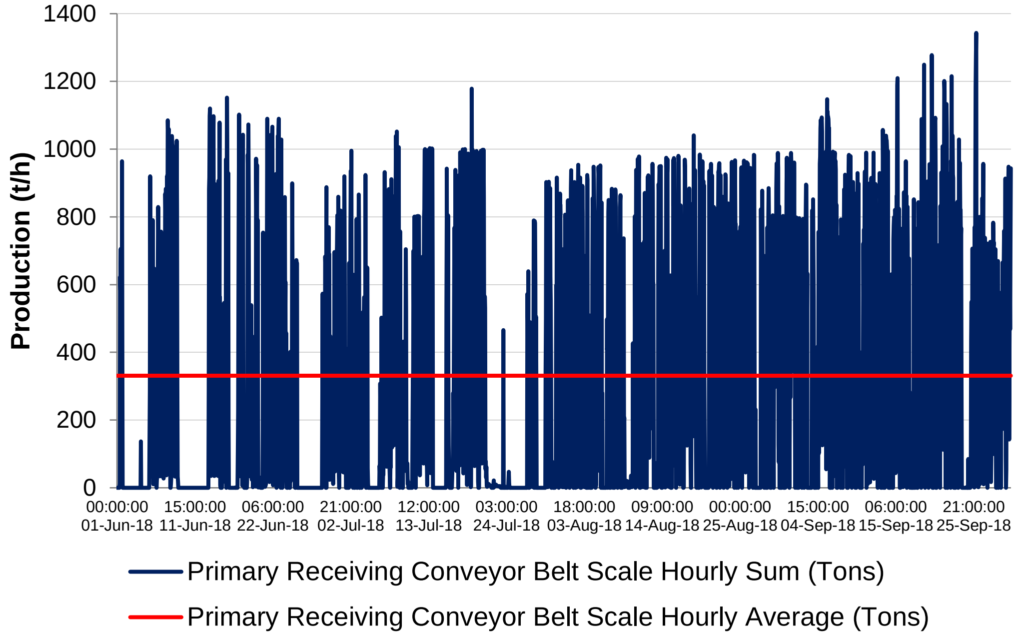


Figure 4.21: Primary Receiving Conveyor Belt Scale Readings from June 2018 to September 2018

The average production was calculated to be 331 t/h. Figure 4.22 shows the production calculated using the Stacker Feed Conveyor belt scale readings.

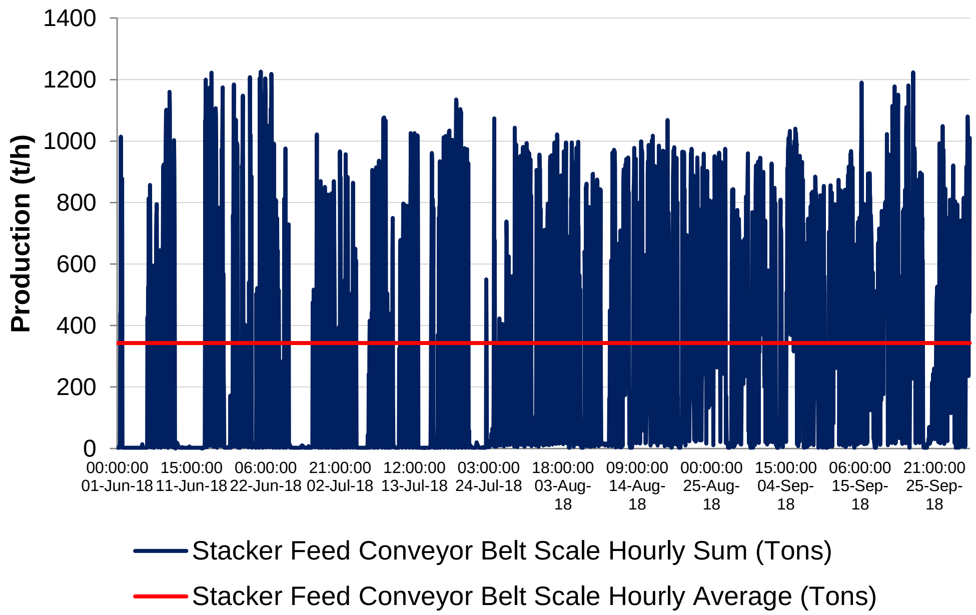


Figure 4.22: Stacker Feed Conveyor Belt Scale Readings from June 2018 to September 2018

The average production was calculated to be 343 t/h. The production difference between the Primary Receiving Conveyor and Stacker Feed Conveyor was 12 t/h (within ± 4% of each other). The calculated production was, therefore, at an acceptable level of accuracy. Figure 4.23 shows the tonnes per day processed by the BMH system for September 2018.

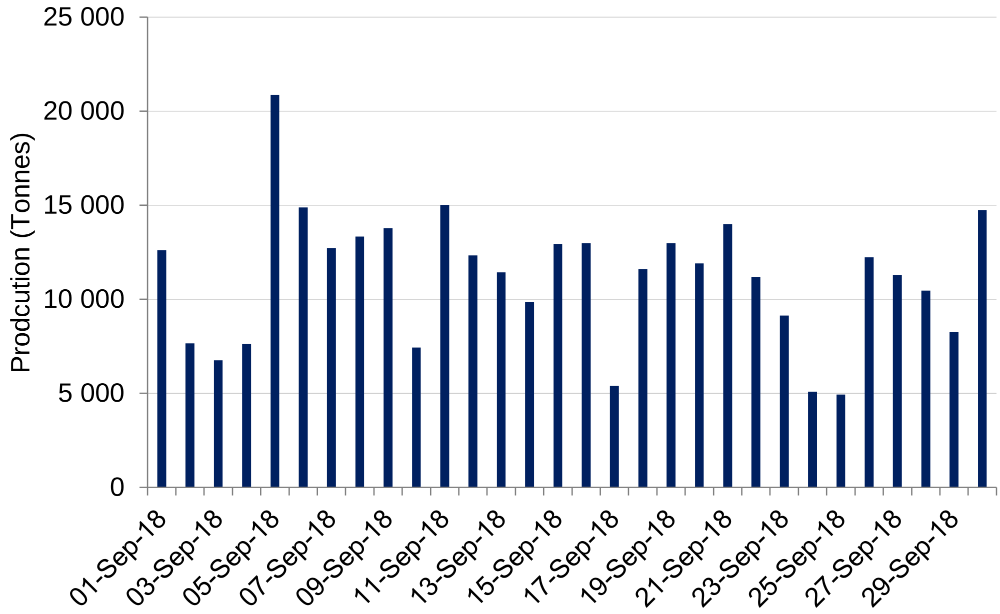


Figure 4.23: BMH Tonnes Per Day Processed During September 2018

On one specific day, ± 20 000 t was achieved, which confirms that the BMH system can process the nominal daily production from the mine (19 684 t).

Data Analysis

The information on Minfo correlates well with the belt scale information on the mine SCADA system (Figure 4.20). The difference between the production calculated using the Primary Receiving Conveyor belt scale readings and Stacker Feed Conveyor belt scales was within ± 4% of each other, with reference to Figure 4.21 and Figure 4.22. The calculated production is considered accurate. Table 4.6 shows a comparison between the actual vs. planned feed rate to the Raw Coal Stockpile.

Table 4.6: Actual vs. Planned Feed Rate to the Raw Coal Stockpile

Actual or Planned	Probability (Risk)	Production (t/h)
Actual	Max.	> 1 263
	P(95)	343
Planned	Max.	1 263
	P(95)	1 022

The Primary Receiving Conveyor belt scale average production recorded during the validation period was 34% of the nominal (1 022 t/h) planned capacity of the BMH system (Figure 4.21). The planned peak capacity of 1 263 t/h was achieved in practice (Figure 4.21 and Figure 4.22). Figure 4.23 shows that ± 20 000 t was processed in one day, which indicates that the system can perform according to the design.

4.4 DMS Plant – Simulation Input Comparison

4.4.1 DOT

Data Collection

The downtimes from 1 June 2018 to 30 September 2018 recorded by the mine were analysed (Figure 4.24). As with the BMH, the same process was used to record and document the downtimes.

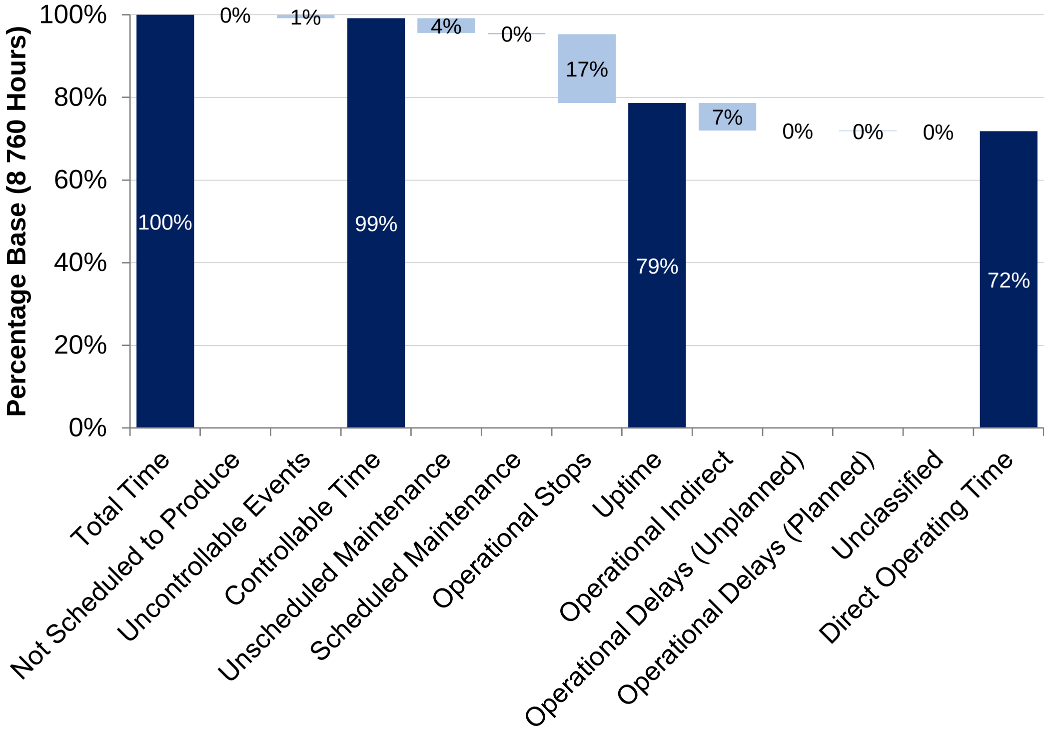


Figure 4.24: DMS Time Model from June 2018 to September 2018

Controllable Time was calculated at 99%, Uptime at 79%, and DOT at 72%.

Data Analysis

The actual vs. planned downtimes were compared, as shown in Table 4.7.

Table 4.7: DMS DOT Comparison (Actual vs. Planned)

No.	Description	Percentage of 8 760 Hours (Actual)	Percentage of 8 760 Hours (Planned)
A	Total Time	100%	100%
B	Not Scheduled to Produce	0%	3%
C	Uncontrollable Events	1%	0%
D	Controllable Time	99%	96%
E	Unscheduled Maintenance	4%	10%
F	Scheduled Maintenance	0%	6%
G	Operational Stops	17%	2%
H	Uptime	79%	78%
I	Operational Indirect	7%	1%
J	Operational Delays (Unplanned)	0%	0%
K	Operational Delays (Planned)	0%	0%
L	Unclassified	0%	0%
M	DOT	72%	76%

No time was allocated to Not Scheduled to Produce in this case. This is as opposed to the 3% allocated in the previous exercise (Figure 3.15). There were no Uncontrollable Events booked compared to the 1% allocation made previously. This resulted in Controllable Time being 3% higher than the previous value (96%). There were large variances in Unscheduled Maintenance (6%), Scheduled Maintenance (6%), and Operational Stops (15%) compared to the previous calculations. Although large, the variances had a negligible impact on the Uptime difference, which was 1%. Operational Indirect was 6% higher than previous, which resulted in DOT being 4% higher than the previous estimate.

4.4.2 Feed Rate to the DMS Plant

Data Collection

FTP information was obtained from the Minfo system. The Plant Feed Conveyor Belt Scale readings were also obtained from the mine SCADA system. This information was compared in Figure 4.25.

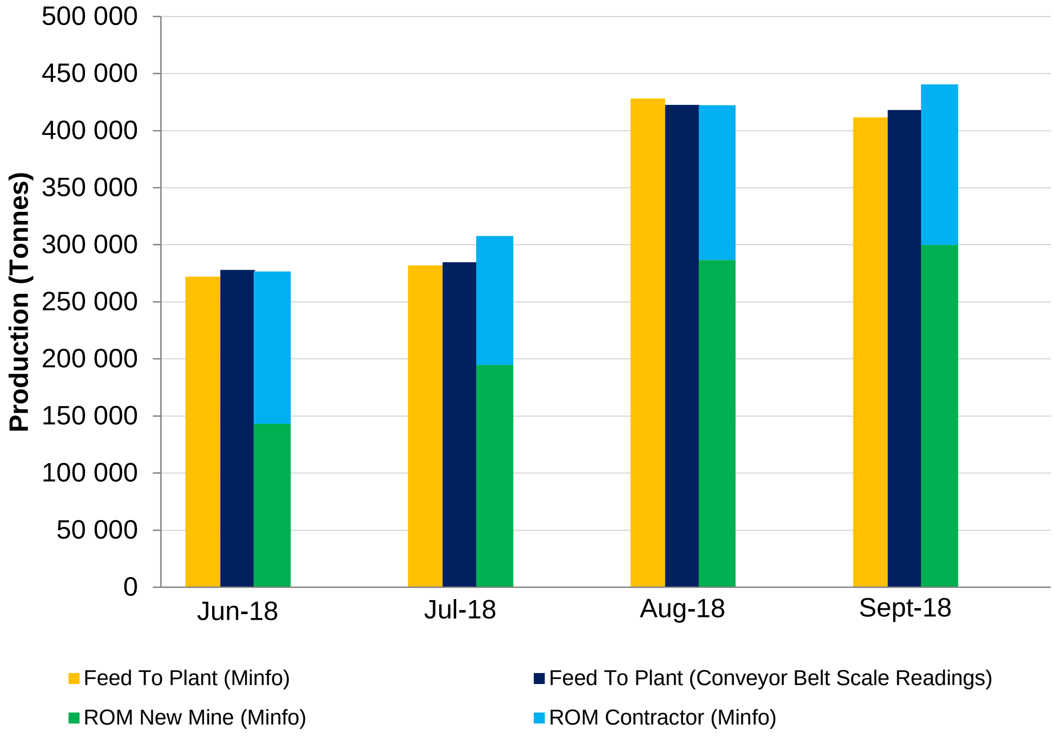


Figure 4.25: DMS Plant Feed Tonnage Comparison

ROM Contractor (Minfo) represents the ROM volumes mined, crushed and supplied to the DMS Plant from the existing mine. These ROM volumes were fed onto the Stacker Feed Conveyor via a temporary material handling system. Figure 4.26 shows the actual production of the DMS Plant compared with the monthly average target (480 750 t) required to meet the yearly production target of 5.769 Mtpa.

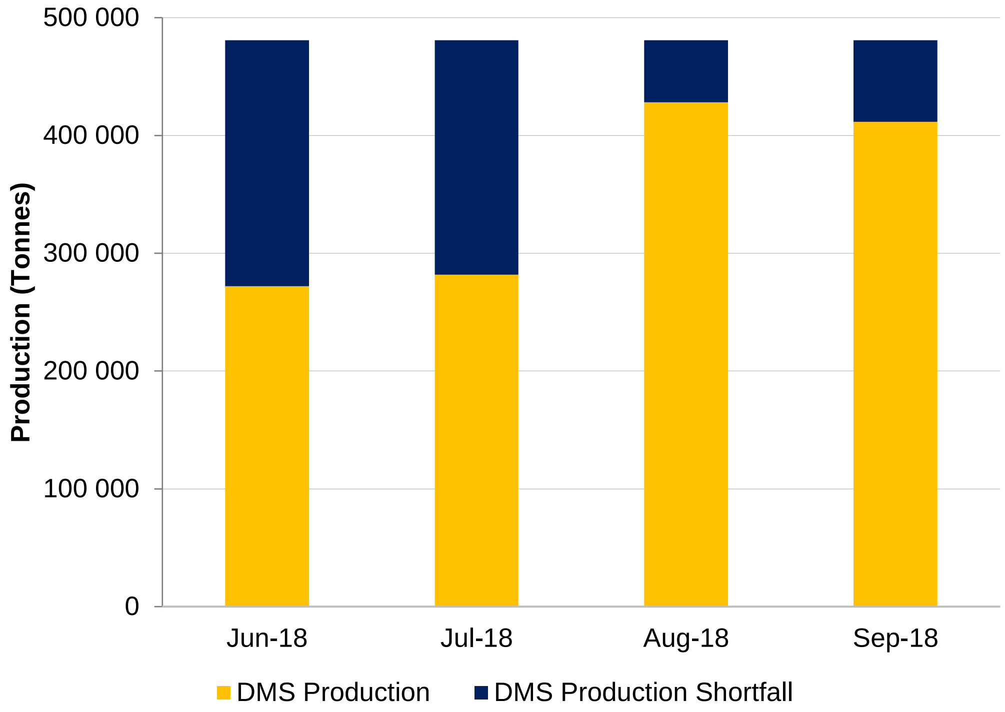


Figure 4.26: DMS Plant Production Performance

In total for the validation period, actual production was 28% below the production target leading up to 5.769 Mtpa. Figure 4.27 shows the tonnes per day processed by the DMS Plant for September 2018.

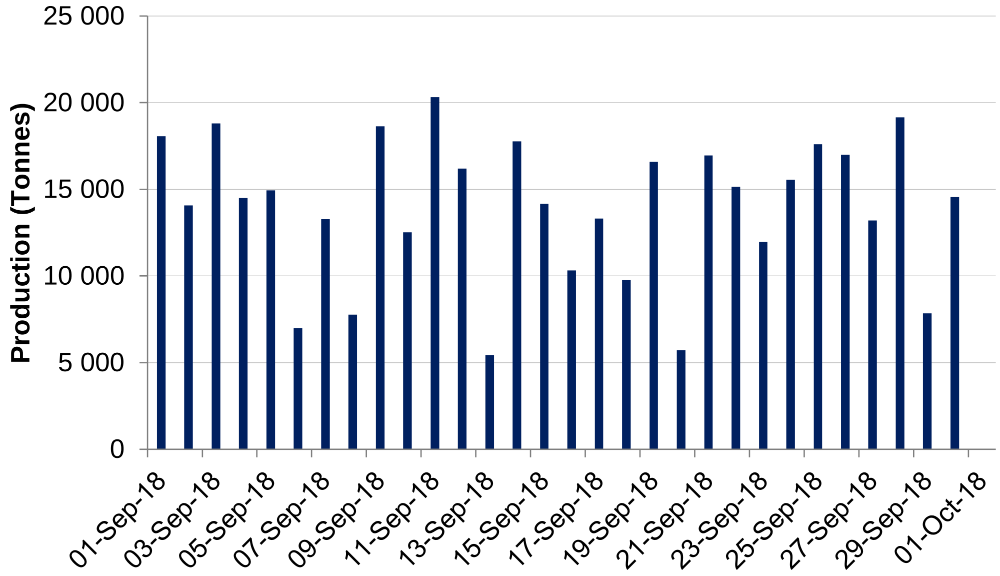


Figure 4.27: DMS Plant Tonnes Per Day Processed During September 2018

The Feed To Plant Conveyor belt scale readings are plotted in Figure 4.28 below.

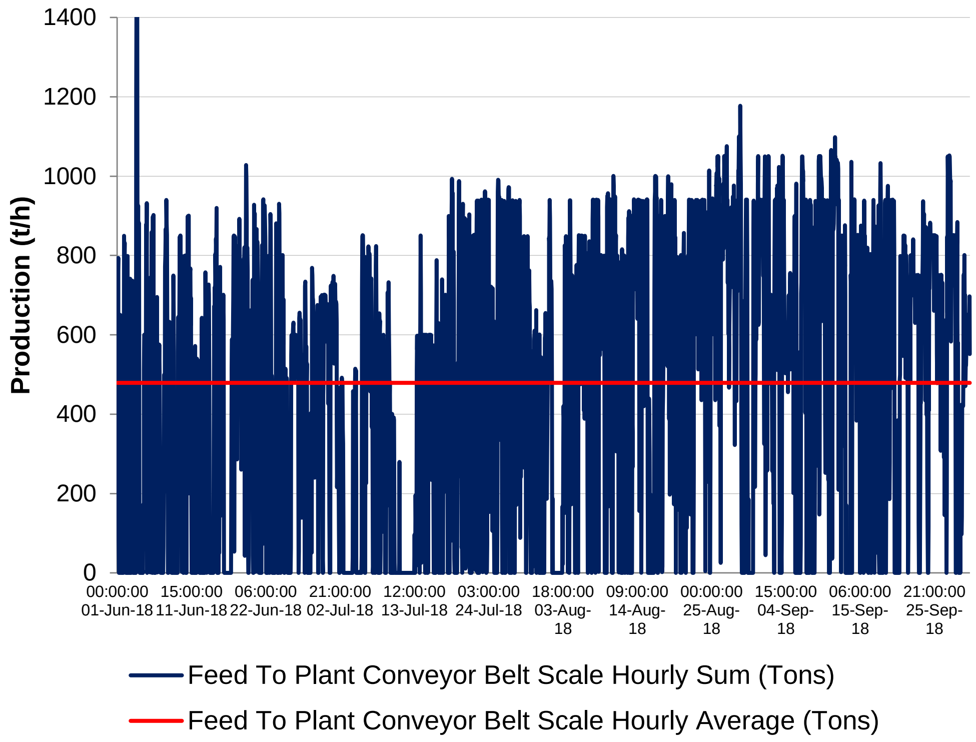


Figure 4.28: Feed to Plant Belt Scale Readings from June 2018 to September 2018

The average production achieved by the DMS Plant was 479 t/h.

Data Analysis

There were two sources of ROM supplied to the DMS Plant from the existing and new mines. The ROM volumes from the existing mine comprised 38% of the FTP on average. There was an average of 1% difference between the Minfo information and the Feed To Plant Conveyor Belt Scale readings. The DMS Plant did not run at capacity during the validation period, and production was below the 480 750 t average target per month to meet 5.769 Mtpa. However, the DMS Plant did achieve ± 20 000 t in September 2018. In Table 4.8, the actual vs. planned feed rate to the DMS Plant was compared.

Table 4.8: Actual vs. Planned Feed Rate to DMS Plant

Actual or Planned	Probability (Risk)	Production (t/h)
Actual	Max.	> 968
	P(95)	479
Planned	Max.	968
	P(95)	861

The average production achieved during the validation exercise was 479 t/h which was 56% of the nominal rate (861 t/h). However, there were a few instances in which the DMS Plant exceeded the peak rate of 968 t/h (Figure 4.28). The peak Reclaimer rate of 948 t/h was also exceeded.

4.5 Overall System – Simulation Output Comparison

4.5.1 Data Collected

The daily tonnages to the temporary ROM Stockpile/Tip from Minfo together with the readings from the Primary Receiving Conveyor belt scale and the Feed To Plant Belt Scale were analysed collectively. The top 20% of the production figures from each system were identified (Table 4.9). The ROM volumes supplied by the Contractor utilised at the existing mine was also considered.

Table 4.9: Best Combination of Production Figures between the Mine, BMH and DMS Systems

Date	ROM Stockpile/Tip (t)	Prim. Rec. Conveyor (t)	FTP Conveyor (t)	ROM Contractor (t)
25-Aug-18	11 777	14 952	21 087	6 384
01-Sep-18	19 350	12 599	18 062	7 239
09-Sep-18	14 400	13 780	18 648	3 857
12-Sep-18	12 000	12 340	16 195	5 225
19-Sep-18	21 300	12 983	16 593	4 180

4.5.2 Data Analysis

The mine and the DMS Plant performed the best collectively on 1 September 2018 processing ± 19 000 t and ± 18 000 t respectively (Table 4.8). The BMH system processed ± 13 000 t on this specific day, but is capable of processing in access of 20 000 t, as shown in Figure 4.23. Table 4.10 shows a comparison between the planned and actual average production of each sub-system.

Table 4.10: Sub-system Average Production Comparison

Actual or Planned	Mine Average Production (t/h)	BMH Average Production (t/h)	DMS Plant Average Production (t/h)
Actual	569	343	479
Planned	937	1 022	861

The difference between the average production from the mine and the BMH system was compensated through the use of a temporary ROM Stockpile which was not part of the project plan and scope. The DMS Plant ran at higher production than the BMH system as the feed to the DMS Plant from

Resource 2 was supplemented with volumes from Resource 1 (contractor mining).

4.6 Chapter Conclusions

The buffer management for the pre-stripping (prior to drilling), truck and shovel (overburden) and coal drilling activities were managed well by the mine. However, buffer management for the drilling and blasting, dozing and truck and shovel (coal) activities were inadequate. This could have led to the mine not meeting targets as shown in Figure 4.18. The mining time model DOT calculation closely resembled the previous calculation conducted during simulation development, but the use of the CAT 994 FEL as an extra loader and not a spare machine resulted in COT being 19% higher than previously calculated. The average of the best (top 10) truck uptimes achieved is in line with the 20.4 hours previously calculated. The maximum coaling production rate of 1 263 t/h was achievable although the mine achieved even higher rates using two excavators and the FEL at times. It was not planned during the LOM extension project phase to use more than one excavator on coal. The mine achieved design capacity and produced ± 20 000 tonnes per day (t/d) on three days during the validation period, although the average daily production was only 8 101 t.

Time modelling on the BMH system conducted previously was confirmed to be within 2% of the validation. Although the BMH system effective production (t/h) was 34% of nominal capacity (1050 t/h), it is capable of delivering ± 20 000 t over a 24-hour period. The DOT for the DMS Plant was calculated to be 4% higher than the previous calculation. Production losses due to poor materials handling value chain performance were minimised through the mining of Resource 1 by a contractor. These volumes were not part of the LOM extension business case and plan. Even with the supply of additional ROM volumes, the DMS Plant did not meet monthly average production targets. However, the DMS Plant did process ± 20 000 t, an indication that sufficient capacity exists to process the average daily production from the mine. The materials handling value chain appears capable of meeting the performance predicted by the dynamic simulation as each sub-system had proven that production of more than 20 000 t/d can be achieved.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research report showed that simulation is a powerful tool and can add value to a project or operation. Simulation allows for the testing of new systems prior to implementation. It can provide insight into both simple and complex systems at a minimum cost, which is small (less than 1%) in comparison to the capital investment required for a new project. Simulation can be used to improve system performance and to solve many types of problems through its ability to run sensitivity analyses for different scenarios. Systems which are critical to production can be analysed without conducting trials on the actual system.

Large mining conglomerates have a fixed amount of capital available each year for expenditure on projects, if any. Only the best projects are approved for implementation. A dynamic simulation of a mine materials handling value chain is a tool that can further motivate the approval of a project. Due to the scarcity of capital, it is important that the mine performs after project approval. Coal Mine A was originally commissioned to extract coal from Resource 1 and did not perform as planned since the commissioning phase. Emphasis is placed on the mitigation of the risk of poor performance post project implementation approval, during the Coal Mine A LOM extension project study phases which were undertaken to prove viability in the mining of Resource 2. The risk of lower production output post project implementation was mitigated to a certain extent because similar mining activities were to be employed at the new mine.

The materials handling value chain consisted of the mine, the BMH system and the DMS Plant. The DMS Plant was the most expensive component in the materials handling value chain and was the CCR. The DMS Plant had to maintain a high availability, and downstream components had to be designed such that the DMS Plant runs at capacity when available. There was a need to integrate the mine, the BMH and the DMS Plant designs via a dynamic simulation to confirm that the complete system can deliver the design production target. Dynamic simulation is also used to reduce production costs and maximise equipment availability in existing systems.

A few publications have been identified which explains the work conducted on mine dynamic simulations, but there is a limited amount of information available on the approach and methods used and simulation validation. No literature was identified which explains the best method of simulating a mine materials handling value chain. The approach to the Gensym G2 dynamic simulation conducted for the Coal Mine A LOM extension project was new and not used at other mines in South Africa. Project time constraints necessitated the use of a "Black Box" model to model the DMS Plant and the integration of a mining variable feed rate input file, generated in Palisade's @RISK software, into Gensym G2. The need to validate the simulation was paramount, as this work could make a significant contribution to the mining industry and stress the importance of validation and post project appraisals.

The presentation of the workings of a simulation to stakeholders is more important than the numerical outputs generated by the simulation. Animation is one of the tools which are available for presentation purposes. Simulation developers must be competent and experienced in the specific field of simulation and have good communication skills such that the description of the simulation can be properly articulated to stakeholders and a meticulous review can be conducted. TOC principles which stress the need to determine the bottleneck of a system and to subordinate all other processors to the bottleneck should be applied to a mine plan to increase confidence levels in achieving planned production. There are many advantages and disadvantages of M&S, but the advantages clearly outweigh the disadvantages.

Verification and validation of simulations and the establishment of credibility in the model are of utmost importance. Verification is the process of checking a model which is conducted by the modeller and a third party if necessary. Validation is the process of ensuring that a model is a precise representation of the system and that it satisfies the objectives of the study. A simulation has credibility if stakeholders accept the model results as correct. A mine dynamic simulation requires a dedicated team of people consisting of mining, materials handling and processing expertise. A competent modeller is required to set-up the simulation. Input is required from an operations team during the simulation process, from the model development phase to the results analysis phase. After the project and operations team have reviewed the dynamic simulation, it is advisable that a third party conduct a scrupulous review of the model and results. Gensym G2 possessed the functionality to simulate the full materials handling value chain of a coal mine which utilises surface (terrace) mining methods. Palisade's @RISK software can be used to determine the buffer capacities of the different mining processes, such that there is a high probability of success in achieving mine design targets when strict buffer management is implemented.

Palisade's @RISK software can be used to produce a file with a variable mine feed rate which can then be utilised in Gensym G2. Potential mining production outcomes can be calculated in Palisade's @RISK software. For the Coal Mine A LOM extension project, the maximum mine feed rate was 1 263 t/h, based on the Hitachi EX3600 Excavator capacity. It was calculated in Palisade's @RISK software that the mine can produce 19 684 t per day at a 95% probability. The calculated Hitachi EX3600 Excavator availability at 66% was only 2% higher than the calculated BMH availability (64%). The BMH system was designed to run at a nominal rate of 1 022 t/h and a peak rate of 1 263 tph. The DMS Plant availability was calculated at 76%. The average annual plant capacity was calculated at 5.769 Mtpa, and maximum annual capacity was calculated at 6.484 Mtpa, including a 5% moisture content. These capacities translate to an average (nominal) feed rate of 861 t/h and a peak rate of 968 t/h. The peak rate of the Reclaimer (948 t/h) was marginally lower than that of the DMS Plant and a Reclaimer upgrade was not deemed necessary.

According to the Gensym G2 simulation, the full materials handling value chain can achieve the average annual production (5.769 Mtpa) without a Buffer Silo. In this scenario, the mining feed rate was variable (at a P95 probability), the BMH system feed rate was set at peak production (1 263 t/h), and the DMS Plant at nominal production (861 t/h). It was calculated that a 3 000 t Buffer Silo could only add ± 20 000 t to annual production, compared to the 5.769 Mtpa estimation. Hence, a Buffer Silo was not considered necessary. The impact a 3 000 t Buffer Silo had on Raw Coal Stockpile level was evaluated. The 3 000 t Buffer Silo did allow the stockpile to run at a higher average level. A "No Silo" scenario together with increasing the mining feed rate to 1 022 t/h and running the DMS Plant at a rate of 968 t/h with the same BMH system production of 1 263 tph was also investigated. In this case, the complete system produced 6.48 Mtpa, which is 12.3% higher than the initial scenario. The variability in the G2 model was tested and was found to be within 1% of each run result and was therefore stable and consistent.

In the rail load-out capacity assessment, the train schedules and arrival times were highly variable. The use of this data in a dynamic model would not have yielded reasonable results, and therefore a static calculation was performed such that the system capacity can be evaluated. The required time between trains was calculated to be 14 hours. Historically Coal Mine A had taken an average time of 8 hours and 20 minutes to handle and load trains and therefore performed well within the 14-hour requirement. Product stockpile capacities were assessed, and space existed to store more than 500 Kt of product. The product stockpile capacities were therefore adequate.

Coal Mine A had good systems in place to regularly record and report on mining activity buffer management. Aerial photography was conducted and incorporated on drawings together with the lengths of the buffers of the different mining activities. These drawings were regularly distributed to the mine operations management team. The required buffer length per mining activity, which was calculated in Palisade's @RISK software considered the worst-case stratigraphy of the resource which consisted of Topsoil, Softs, Hard Burden, No. 4 Seam, Hard Inter Burden, No. 2 Seam, Parting, and No. 1 Seam. During the validation period, the geology was different and consisted of Topsoil, Softs, Hard Burden, No. 2 Seam, Parting, and No. 1 Seam, and the required buffers had to be adapted such that the validation work can be conducted. There were various deficiencies identified in the mining activity buffer management, although the buffers for topsoil stripping, overburden truck and shovel and coal drilling activities were sufficient. The drilling and blasting buffer was insufficient for the full duration of the validation period. The dozing buffer was also insufficient for most of the validation period, apart from a duration of 10 days. The coal to be mined buffer was also insufficient for most of the time (14 weeks). A potential reason for the substandard buffer management was the unplanned use of truck and shovel capacity for overburden removal instead of the use of drilling and blasting and dozing capacity, which decreased the capacity available for the truck and shovel of coal. Another reason could be coal drills poor performance, which impacted the volume of coal available for trucks and shovels operations.

The Hitachi EX3600 Excavator DOT, which was calculated during the validation exercise was 4% lower than the previous estimate, but COT was 19% higher as a result of the CAT 994 FEL being used 23% of the time more than previously estimated. This eludes to the fact the CAT 994 FEL was not used as a spare machine as originally planned and was used in parallel with the other excavators. A ROM Stockpile near the ROM Tip was not originally planned as per the original materials handling value chain design. A decision was taken to create the stockpile to buffer the mining processes from the BMH system during the commissioning period which took longer than expected. This resulted in the requirement for additional equipment which could have attributed to low mining production rates.

The average (20.3 hours) of the top 10 best uptimes that the Komatsu 730e Trucks achieved during the validation period was in line with the previous calculation (20.4 hours). It was clear that the mine did not stick to the coaling plan as per the mine design having used two and sometimes three pieces of loading equipment in parallel. With one excavator, the mine achieved production of 1 263 tph which was in line with the maximum rate used in the feasibility study. The use of two pieces of loading equipment yielded production of only 1 739 t/h and three yielded production of only 1 502 t/h. The average daily production that the mine produced for the validation period was only 8 101 t, compared to the 19 684 t per day the mine was designed to produce. However, on three separate days in September 2018, the mine did achieve an average of ± 21 000 t which was in-line with the calculation conducted in the feasibility phase of Coal Mine A.

The BMH DOT calculated during the validation period was 2% lower than the previous calculation. The primary receiving conveyor belt scale, stacker feed conveyor belt scale and Minfo system readings when compared were found to have an acceptable level of accuracy. The Minfo information and the Primary Receiving Conveyor Belt Scale readings had an average difference of 3%, and the Primary Receiving Conveyor Belt Scale readings and the Stacker Feed Conveyor Belt Scale readings had an average difference of 5%, which were acceptable. The average production the BMH system achieved was 30% below the nominal capacity during the validation period. Nevertheless, there were instances during September 2018 when the system did run at the nominal capacity of 1 050 t/h, and one instance when the system processed ± 20 000 t in one day, which matched the nominal design capacity of the mine.

The DMS Plant DOT was found to be 4% higher than the previous calculation. The continuation of the mining of Resource 1 post relocation of the mining equipment to Resource 2 was not part of the project business case. Nevertheless, the operations team had commissioned a mining contractor to continue with the mining of Resource 1, and the DMS Plant was fed with this coal (38% of total FTP) during the validation period. This might have been a factor in the decision not to push production from Resource 2 and could be a reason for the poor mining performance at Resource 2.

Despite the alternate source of coal, the DMS Plant did not perform at capacity and meet monthly production targets. It was shown that the DMS Plant can match nominal mine design production (± 20 000 t), when this was achieved in September 2018. The average production the DMS Plant achieved was 479 t/h, which was 56% of nominal production required to meet the annual target of 5.769 Mtpa. There were a few instances identified in which the DMS Plant exceeded the peak rate of 968 t/h. The individual system components (Mine, BMH System, and DMS Plant) are individually capable of producing ± 20 000 t. The view is that, with strict buffer management, the full materials handling value chain is capable of producing ± 20 000 t consistently and can achieve the mine design production of 5.769 Mtpa, as predicted by the dynamic simulation.

5.2 Recommendations Stemming from the Research

5.2.1 Mining of Resource 1

The mine had an alternative resource of coal during the validation period, and this could be the reason for the poor performance in the mining of Resource 2. The production tonnages from Resource 1 post mining equipment relocation were not factored into the LOM extension project business case, and this should have been part of the mine planning. The task of measuring and confirming mine performance would have then been a straightforward exercise. A trade-off study to compare owner mining vs. contractor mining to complete the mining of Resource 1 was not conducted, and the decision to opt for contractor mining was questionable. An option would have been to keep the mining equipment at Resource 1 for a longer period and complete the mining of Resource 1, before moving to Resource 2. The deviation in plan still did not allow the DMS Plant to run at full capacity from June 2018 to September 2018. It is recommended that the simulation validation exercise be revisited after contractor mining of Resource 1 has been completed.

5.2.2 Mine Activity Buffer Management

One of the operational performance issues identified was the buffer management of the different mining activities. Upon commissioning, the mine was not set up according to the recommendations from the TOC work conducted, and the mine thus did not have the required buffers in place. The mine could have had a sufficient amount of coal exposed because of the box-cut construction which was in the project scope. The possible use of truck and shovel capacity to move overburden instead of drilling and blasting, then dozing, could have resulted in insufficient capacity for the truck and shovel of coal activity. The coal drills could also have performed unsatisfactorily, which aggravated the performance issue. Coal Mine A should place more emphasis on configuring the mine such that the mine is set up according to the TOC study recommendations. The view was that if the mine conducts proper buffer management and mines to plan, not plan to mine, the system can perform to design expectations.

5.2.3 Use of More Than One Excavator on Coaling

The mine deviated from the mine plan and used more than one excavator and/or FEL on coaling activities. This approach was counterproductive as the mine did not achieve double or triple the achievable mining feed rate with one additional excavator or FEL. It is recommended that the mine consult with the mine design team if there is merit in changing the plan and using more than one excavator.

5.2.4 Use of ROM Stockpile

In the original mine plan, coal was planned to be loaded directly from the pit and not from a ROM Stockpile. A ROM Stockpile was not included as part of the scope of the project. It is understandable that a “temporary” ROM Stockpile was put in place to buffer the mining operation from the BMH process during commissioning while various operational issues were resolved on the BMH System. However, there was still coal left at Resource 1, which served to supplement the volumes from Resource 2. The view was that the potential need for a temporary ROM Stockpile should have been factored into the planning and the alternative of keeping the mining equipment for a longer time at Resource 1 should have been considered.

5.3 Recommendations for Future Work

The feasibility of developing a single model of the complete system should be investigated. Sustained performance levels in the mine’s materials handling value stream are yet to be confirmed. It is recommended that this dynamic simulation validation be revisited and updated post the mining of Resource 1. It is also recommended that the validation exercise be conducted over a 12-month period. This will confirm beyond doubt that the approach taken for the dynamic simulation of Coal Mine A LOM extension project was accurate, effective and reliable.

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