UNLOCKING VALUE THROUGH IMPROVED PRODUCTION DECISION MAKING – A TRACKLESS MINING SYSTEMS ANALYSIS

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22 August 2018

DECLARATION

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

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(*Ethics clearance number:* ***MIA-009/2018***)

ABSTRACT

This study was based on the hypothesis that there are opportunities to maximize production outputs in many existing underground hard rock trackless mining systems using the same or less resources by improvement in decision making paradigms. This is very important in the current operating environments of uncertainties and continued drop in metal prices.

The project main goal was thus to carry out a detailed investigation of trackless mining production systems and test how to maximize output by focusing on three objectives, namely: analyzing key technical factors that impact the production rates in terms of tons per hour, identifying major operational activities which impact effective equipment operating hours, and identifying decision support systems (DSS) to improve operational decision making.

Regarding the first objective (production rates), through the analysis of trackless mining as a serial production system, it was shown that production rates could be increased by focusing at system level, process level and work station/equipment level decisions. System level decisions must minimize the total residence time of the material (ore) in transit or work in process(WIP). This will open capacity for generating more ore. Process level decisions must reduce the gross cycle times at the work stations to equal or be below the Takt times inorder to smoothen production flow. Takt time is an important factor in a production system which shows the maximum cycle time allowed to meet the daily demand. The third level focuses on the capability of the mining equipment itself through decisions that improves the reliability, maintainability and capacity. Decision tables based on reducing the equipment failure rates (λ), improving the repair rates (μ) and the cycle times were developed to aid in making the reliability, maintainability or capacity decisions.

For the second objective (operational activities), the focus is to maximize effective operating times of the equipment through reduction of delays. The study shows this can be achieved through use of real-time decision support systems (DSS) for better control of the operations. The third objective was able to identify functional modern DSS that can be implemented in trackless mining.

Effectively, the study was able to highlight opportunities of generating extra capacity for trackless mines at same or less resources by focusing on the above three objectives.

DEDICATION

This report is dedicated to my wife Patricia and our three lovely children, Praise Mwaitaishe, Tinevimbonashe Rachel and Prince Nyasha.

I am convinced that in God there is no failure, there is enough Grace to succeed.

Christopher Mukonoweshuro

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History has it on record that no great work is ever achieved by an individual. Similarly, this product is a result of the help, support, encouragement and commitment I received from so many dear people who have made it possible for me to complete this work.

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Christopher Mukonoweshuro
22 August 2018

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ABBREVIATIONS

ADT	Articulated dump truck
CAD	Computer Aided Dispatch System
CCTV	Closed Circuit Television
CIM	Computer Integrated Manufacturing
CMMS	Computerized Maintenance Management System
DSS	Decision Support System
EEU	Effective Equipment Utilization
eFFBD	Enhanced Functional Flow Block Diagram
ERP	Enterprise Resource Planning System
EOS	End of Shift
ENG	Engineering
ES	Expert System
EY	Ernest and Young
FDM	Frequency Division Multiplexing
FIFO	First in First Out
HMI	Human Machine Interface
IDEF0	Integration Definition for Process Modelling
ISO	International Standardization Organization
KPI	Key Performance Indicator
LAN	Local Area Network
LHD	Load haul dumper
LME	London Metal Exchange
LSE	Lean system engineering
MAP	Manufacturing Automation Protocol
MCC	Mine Operations Control Centre
MDE	Mobile Diesel Equipment
ME-DSS	Mine Expert Decision Support System
MES	Manufacturing Execution System
MineOps	Mine Operations System
MIC	Miner in Charge

MIS	Management Information System
MIT	Material in Transit
MTBF	Mean time between failures
MTTR	Mean time to repair
NIOSH	National Institute of Occupational Safety and Health (Australia)
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OP	Operational
OSI	Open Systems Interconnection (OSI) architecture
OTN	Open Transport Network
PLC	Programmable Logic Controller
PM	Planned Maintenance
PPT	Planned Production Time
PTO	Planned Task Observations
PWC	Price Waterhouse Coopers
RFID	Radio Frequency Identification
ROM	Run of Mine
SCADA	Supervisory Control and Data Acquisition
SE	System Engineering
SLOS	Sub-level Open Stoping
SOS	Start of Shift
TOC	Theory of Constraints
TON	Metric ton
TT	Takt time
UG	Underground
UTO	Unplanned Task Observation
VSM	Value Stream Map
WAN	Wide Area Network
WIP	Work in Progress
VDT	Value Driver Tree
YTD	Year to Date

LIST OF SYMBOLS

λ	Failure rate (number of failures per unit time)
μ	repair rate (number of repairs per unit time)
Л	Effective process recovery, an efficiency factor
AT	Available hours
Av	% Availability
B	The buffer (storage) size B is the number of LS the storage can hold
BF	Bucket or Fill Factor (tons/load) – an efficiency factor
CO	Changeover time
CT	Cycle Time of the station to move a LS, e.g. minutes/load
D	Average Delay Time for material (ore) in transit (MIT)
DT	Downtime hours
h	hour
LS	Lot size, which is the target quantity produced per cycle of production (e.g. Loads/h)
MTBF	Mean operating time between failures (1/ λ)
MTTR	Mean time to repair after failure of system elements (mean downtime) (1/ μ)
OT	Operating hours per day - actual time station is being used for production purposes
PPT	Planned production time
PS	Rated production speed of a works station – No of jobs or LS per hour without any failures of the work station (rated capacity)
PS_i	Rated production speed of a works station no *i* (*i*=1,2,3,…..)
Q	Production rate - quantity of ore moved or hoisted, in metric tons per unit time (tons/h)
Q_T	Total ton moved per period (in metric tons) (Q_T = Q x h)
S(t)	Material Stock at time, t
SP	Metal selling price, $/ton
t	time
TH	Throughput rate - LS moved per unit time of production (loads/h), considering failures
UP	% uptime of system
UT	% utilization of the system

P	Operating Profit, in US$
R	Total Revenue, in US$
C_T	Total Costs, in US$
M	Total Metal Produced, in metric tons

Statistical symbols

Y	Response (dependent) variables
X	Explanatory (independent or predictor) variables
β_1	Linear regression parameters, constant over all cases
θ	Non-linear regression parameters
ε	Residual (or Random Disturbance or Error) variable which varies over all cases.
$\bar{U}$	Statistical mean
σ	Standard deviation
σ^2	Variance
β_0	Represents the intercept of the best fitting line
r_{xy}	Correlation (Pearson) Coefficient
SS_x	Sum of squares for X variables
SS_y	Sum of squares for Y variables
n	Number of sample pairs analysed
$\sum X$	Sum of explanatory (independent or predictor) variables
$\sum Y$	Sum of response (dependent) variables
$\sum XY$	Sum of product of X and Y
R^2	Coefficient of Determinations or Regression coefficient
SSR	Regression Sum of Squares, SSR = $\sum_{i=1}^{N}[(\hat{Y}\mathrm{i})error-(\bar{Y})error]2$
SST	Total Sum of Squares , SST = $\sum_{i=1}^{N}[(\hat{Y}\mathrm{i})observed-(\bar{Y})observed]2$
$\hat{Y}_i$	Represents the reading at i = 1, 2, 3 ……N
$\bar{Y}$	Represents the mean reading of the population.

1. INTRODUCTION

1.1. INTRODUCTION

Uncertainties in commodity prices globally is putting a lot of pressure on the sustainability of many mining businesses. In the past ten years for example, gold price moving averages dropped by about 18%, platinum by 22%, copper by 43%, and nickel by 63% (LME,2018; Kitco,2018). As the resource industry is becoming more vulnerable to these fluctuating and unpredictable commodity prices, there is a renewed focus across mining businesses on reducing costs and increasing productivities as key factors for sustainability (Durrant-Whyte, et al., 2015).

However, focusing only on reducing costs without increasing volumes realizes marginal benefits and does not give sustainable results (Knights, et al. 2009). Thus, there is increasing need for having different approaches of looking at mining production systems. One way is realizing that improving production volumes is a key economic value driver in the mining business. Investment in new technologies and processes that increase productivity in mining, more so in underground mining, may therefore be considered as an important strategic issue.

This study is based on looking at key factors that optimize the following equation of production:

Production volume (tons) = production rate (tons/h) x Total effective operating hours (h)

The key assumption in the project is that production volumes can be increased by either increasing the production rate of the mine or maximizing the total effective operating hours or both. However in underground, mining is a complex system which makes it not a very easy task to increase the production rates or the total operating hours.

Production rates are basically a function of the capabilities of the equipment and the mining processes. These in turn depends on the mine design factors as well as reliability, maintainability and capacity factors of the various equipment used in the production process. On the other hand, the total operating hours mirrors the overall system’s logistical factors such as reflected in the system delays, system lead times, work in process (WIP) residence times, gross process cycle times and equipment face time. Process buffers (stock piles) are also important as they influence the overall WIP and output rates.

The complexity of underground mining, compared to other industries, arises mainly from issues such as; continuously shifting boundaries, rapid changes in geological conditions, face advances, difficult mining configurations, spatial distribution of equipment and processes, invisibility of activities, batch rather than continuous processes, fluctuating commodity prices, people issues, process/equipment breakdowns and safety risks.

These ever-changing conditions pose serious difficulties in process control and operational decision making since most of the processes are invisible to management as they happen. Most times, the impact of operational decisions is not noticed immediately and deviations from plans are normally noticed 24 hours, a week or a month later making corrective action rather too late.

All these factors impact the production rate or the total operating hours in the mine. Coetzee (2006) alludes that:

> *"The key to unlocking the full potential of mining and manufacturing operations lies in the ability to gain a real-time understanding of what is actually happening in the process and plant. That information needs to be shared with the other important decision makers in real-time, and action should be taken to improve both production performance and bottom line"*(Coetzee, 2006).

Thus, the complexity in geo-configuration of underground mining operations causes difficulties in accessing information in real-time to be able to monitor activities as they happen which have an impact on the production rate or on total hours of operations. Timely and fast decision making is thus a very critical success factor in underground mining systems. Any time wasted in planning and deciding an action underground can mean the difference between success and failure of an operation as well as aversion of disasters and serious accidents.

The mining industry in general is realizing that investment in new technologies and methods that increase mine throughputs and reduce costs is the step change required for a sustainable future. Many available articles and reports such as Durrant-Whyte, et al. (2015) of Mckinsey & Company, Lumley & McKee (2014) of Price Waterhouse Coopers (PWC) and Mitchell & Steen (2014) of Ernest and Young (EY) Consultants, show that acquiring the capability to make right operational decisions faster and quicker has become an important strategic issue for mining operations.

1.2. BACKGROUND TO STUDY – SETTING AND SYSTEM BOUNDARY

1.2.1. Project intent

The main intent of the study was to investigate opportunities for improving productivity in underground trackless mining through identifying some key decision factors that has a major impact on production outputs using the same or lower resources. This was to be achieved through applying the various existing theories of production systems, methods for analysis of stocks and work-in-process (WIP), analysis of system delays and analysis of equipment reliability and maintainability factors.

Through applying this information, it is expected to be invaluable to key mining decision makers, technology developers and system implementers by pointing out some of the areas which still need more focus in the productivity improvement journey.

The research is hinged on the hypothesis that more study still needs to be done to validate the benefits that can be derived through applying of better information and data-driven decisions regarding increasing mining production rates for underground trackless systems.

In general, mines generate a lot of operational data and studies show that this data is rarely used to make better tactical and operational decisions as shown by Durrant-Whyte, et al., (2015). The researcher's observation is that the fast development of new concept of digitization of systems in underground mining is largely driven by technology providers and there is real danger of industry adopting systems and technologies which will not fulfil business needs in case of limited research.

Most companies may feel forced to join the new technologies bandwagon and mine digitization, but many may fail to maximize the possible benefits because there could be no known frameworks to guide the selection of value adding concepts. The following issues therefore present some reasons why the study of this nature needs to be undertaken.

1.2.2. Nature of the problem – the total value at stake

Durrant-Whyte, et al., (2015) indicate that there is up to US$250 billion which can be unlocked in improved operations systems and up to US$100 billion in improving equipment maintenance systems globally in mining, as illustrated in Figure 1.1.

Durrant-Whyte, et al, (2015) also indicates five key areas that are impacted greatest by an improved decision system as being: 1) understanding of the resource base, 2) optimization of equipment and material flow, 3) improved anticipation of failures in the system (predictive systems), 4) increased mechanization and, 5) monitoring of performance in real-time of actual vs plan. Figure 1.1. represent this view.

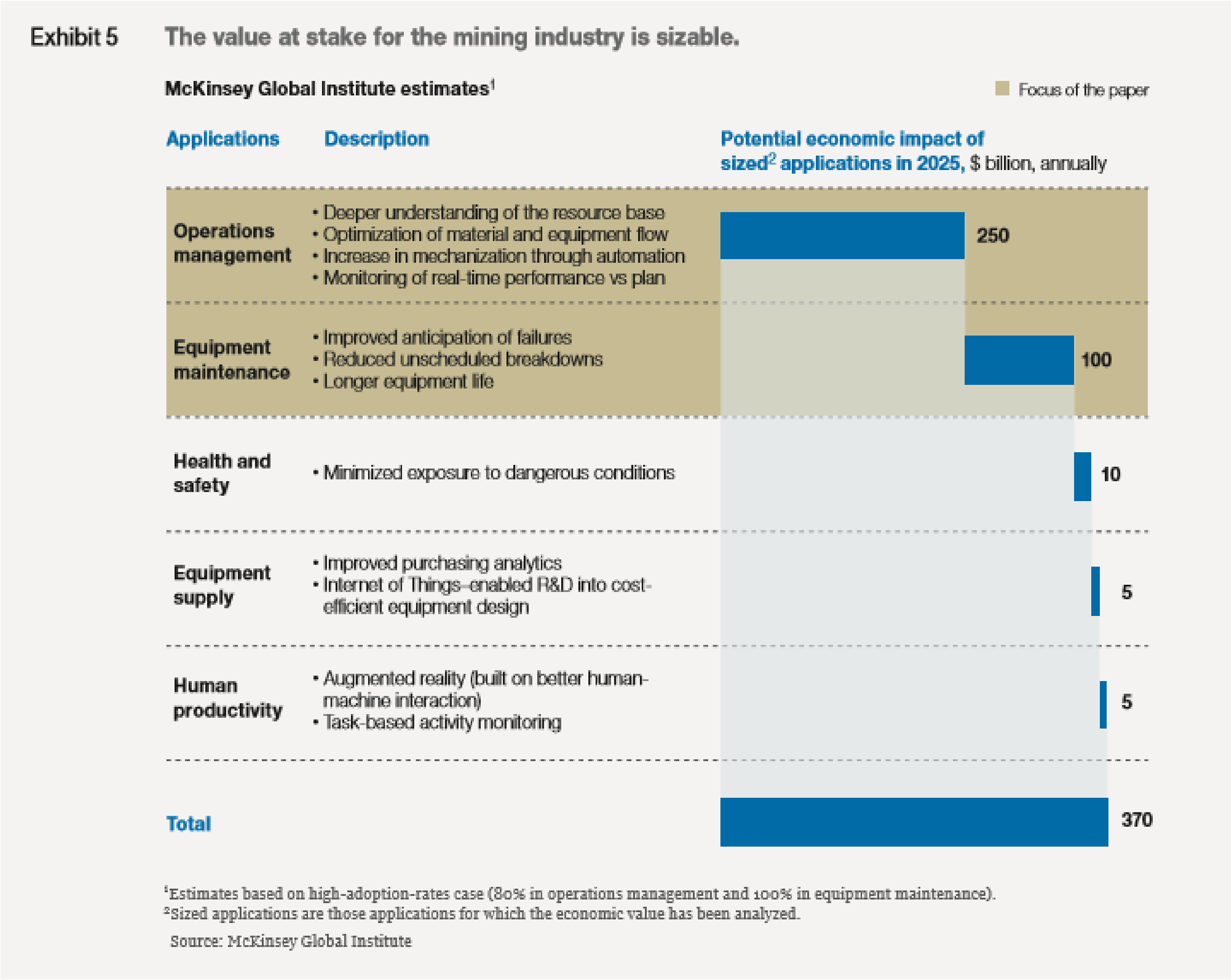


Exhibit 5 The value at stake for the mining industry is sizable.

McKinsey Global Institute estimates[1]

▨ Focus of the paper

Applications	Description	Potential economic impact of sized[2] applications in 2025, $ billion, annually
Operations management	• Deeper understanding of the resource base • Optimization of material and equipment flow • Increase in mechanization through automation • Monitoring of real-time performance vs plan	250
Equipment maintenance	• Improved anticipation of failures • Reduced unscheduled breakdowns • Longer equipment life	100
Health and safety	• Minimized exposure to dangerous conditions	10
Equipment supply	• Improved purchasing analytics • Internet of Things–enabled R&D into cost-efficient equipment design	5
Human productivity	• Augmented reality (built on better human-machine interaction) • Task-based activity monitoring	5
Total		370

[1] Estimates based on high-adoption-rates case (80% in operations management and 100% in equipment maintenance).

[2] Sized applications are those applications for which the economic value has been analyzed.

Source: McKinsey Global Institute

Figure 1.1 – Value of stake in improved mining operations (source – Durrant-Whyte, et al, (2015))

Durrant-Whyte, et al, (2015) report is very important for mining operations to explore these opportunities so that performance can be improved using same resources.

1.2.3. Nature of the problem – lack of live information to support decision making

Through own experience, the researcher noted that although most mining leaders are conscious and accept the importance of improved decision making in underground mining, there seem to be no generic guidelines or publicly available frameworks for adopting and justifying when making business decisions to do with improving overall mine throughputs.

Through experience also, the researcher noted that most excellent mine planning strategies fail at the execution phase when operational decisions are being made at the face because of limited information to make the right action. A Mckinsey & Company report by Durrant-Whyte, et al., 2015 also backs this statement, as illustrated in Figure 1.2 which shows that only 1% of data generated in mining operations is used for decision making globally. This scenario presents a picture of great opportunities for using data to value add in mining processes.

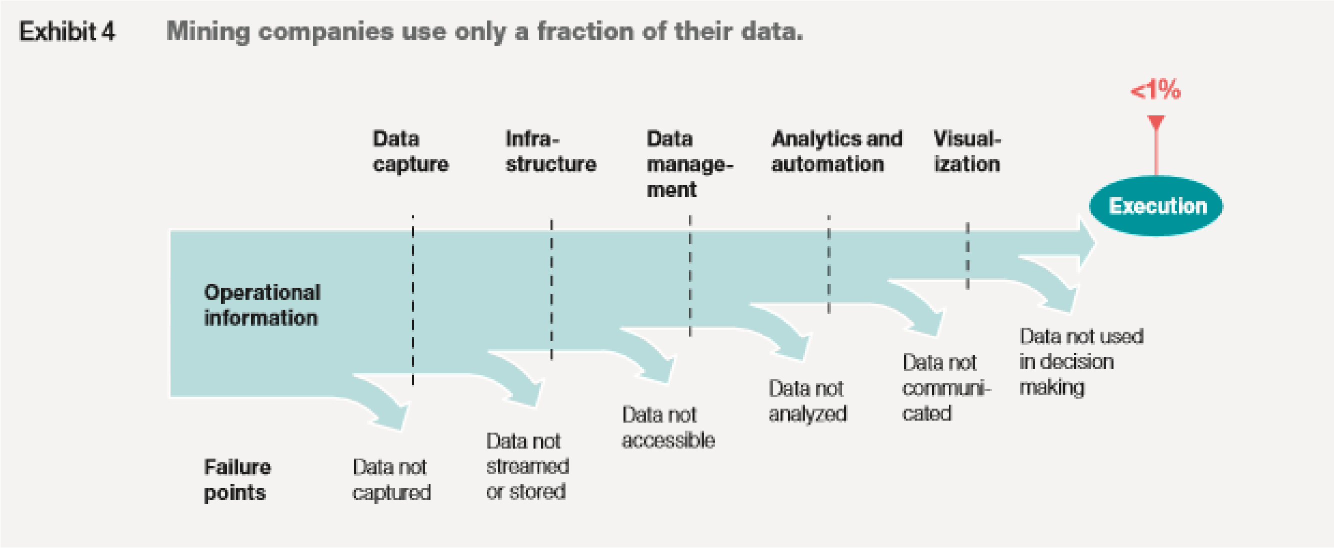


Figure 1.2 Use of operational data in mines [Source – Mckinsey & Company (Durrant-Whyte, et al., 2015)]

Because of complex geographical configuration underground and ever-changing conditions, great difficulties exist for process control and operational decision making due to many activities being invisible to management and supervisors as they happen.

As alluded earlier, most times the impact of an operational decision is not felt immediately. As was observed at MineABC and MineXYZ by the researcher during his employment, deviations from the business plans were only normally noted during planned review meetings at the end of the shift or after 24 hours when corrective action was already too late.

The delays in making decisions at these mines (MineABC and MineXYZ) was noticed to be due to lack of correct data and information to support the decision-making process in time for the team leaders and supervisors on the face to make corrective interventions. The difficult configuration of the underground mining operations also caused a lot challenges in accessing information in real-time to be able to monitor activities as they happen. This is probably a common scenario in most traditional mines.

However, besides lack of data, the availability of correct information is very important to make the right decisions. It was also observed at MineABC and MineXYZ that a lot of time was wasted due to unpredictable daily events such as equipment breakdowns and process delays. Bandyopadhyay et al., (2010) say that if management is made aware of situations on the ground and breakdowns within minutes, attention could quickly be focused on solving the problem which ultimately increases the long-term production and enhancing safety by accurate fast communication means.

An important premise of this study also was that Decision Support Systems (DSS) in real-time would thus help decision makers to monitor events, evaluate, choose and quickly act on alternatives as events unfold in underground operations. DSS have found application in many other industries ((Burstein & Holsapple, 2008)), albeit at a far smaller pace in underground mining systems Bandyopadhyay et al., (2010).

Bandyopadhyay et al., (2010) and NIOSH (2011) show that the slower rate of adoption of the DSS concept in underground mining may be attributed to the complexity in developing technologies which can transmit voice, data and picture/video to and from underground. There may also be a need to break the “traditional mining” culture inherent in some of the older operations that says, “we have always done things this way” as shown by Hall (1996).

1.2.4. Context of the problem - decrease in equipment productivity index in Africa

Analysis reports by Mckinsey & Company (Durrant-Whyte, et al., 2015), Price Waterhouse Coopers (PWC) (Lumley & McKee, 2014) and EY Consultants(Mitchell & Steen, 2014), indicates that there has been a significant decrease in both labour and equipment productivity in the global mining industry as high as 25%, from the year 2000 onwards despite recorded significant improvements in various technology and equipment sizes as indicated in Figure 1.3.

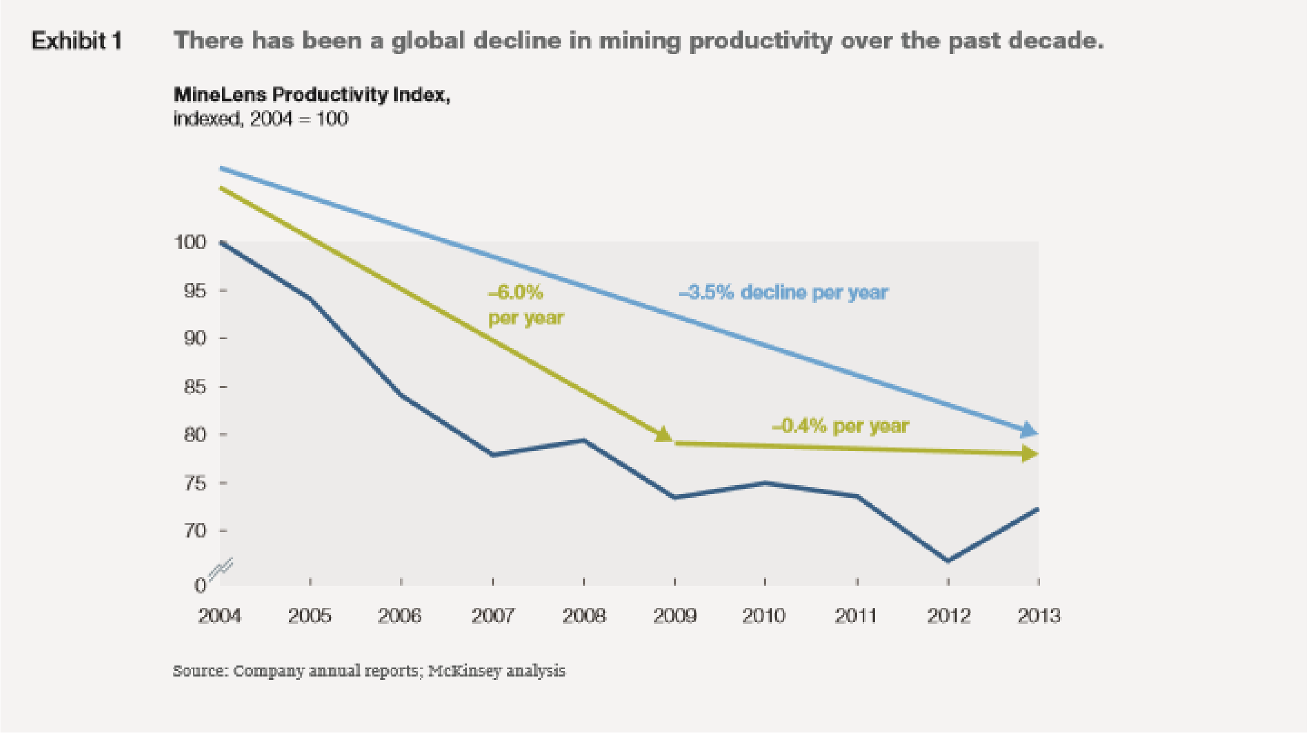


Figure 1.3 – Global Mining Productivity Index [Source – Mckinsey & Partners (Durrant-Whyte, et al., 2015)]

The results also indicate that the equipment productivity index in Africa is the lowest, followed by Australia as indicated in Figures 1.4. This is a quite worrying phenomenon for mining operators, especially in Africa whose economy is highly dependent on commodities for its success, and thus calls for serious strategic interventions.

The reports by EY(Mitchell & Steen, 2014), PWC (Lumley & McKee, 2014) and Mckinsey (Durrant-Whyte, et al., 2015), also advocate that an equipment-level performance data management process and use of data to steer daily decision-making is a key winning business strategy.

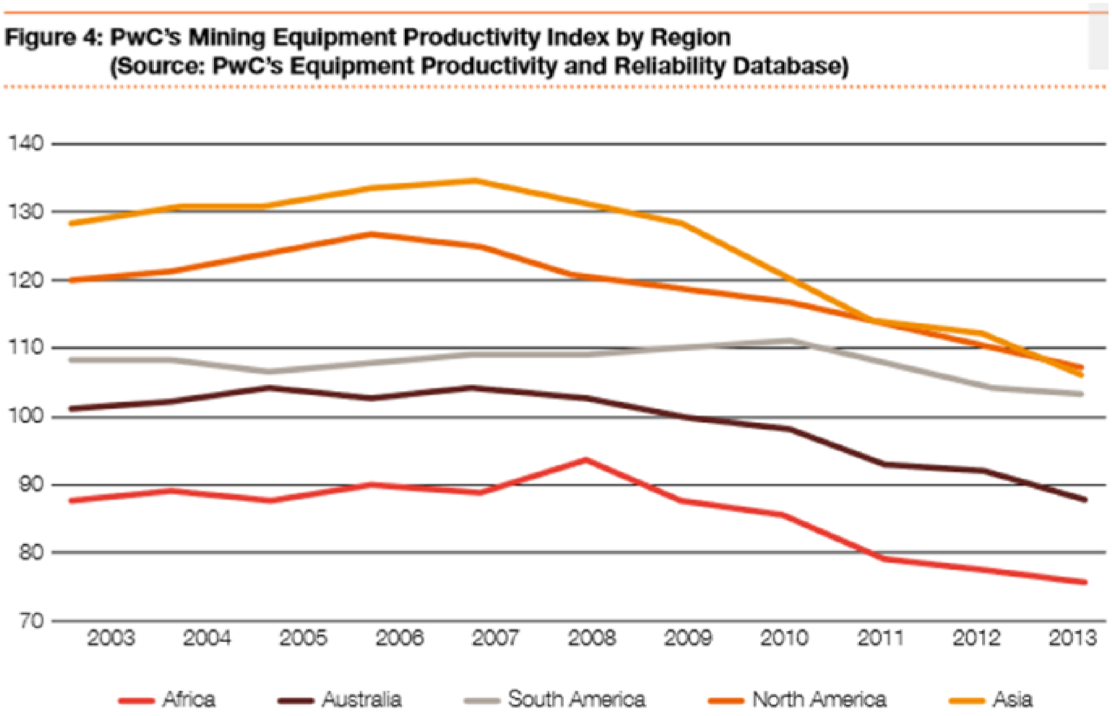


Figure 1.4 –Mining Equipment Productivity Trends [source – PWC (Lumley & McKee, 2014)]

1.2.5. Context of the problem – falling global commodity prices

It can also be noted that the decrease in mining productivity is happening against a backdrop of continuously falling global commodity prices. The October 2015 World Bank commodities report (World Bank Group, 2015) forecasted a 19% decrease in metal prices in 2015/2016 with a downside risk of closures on high cost producing mines.

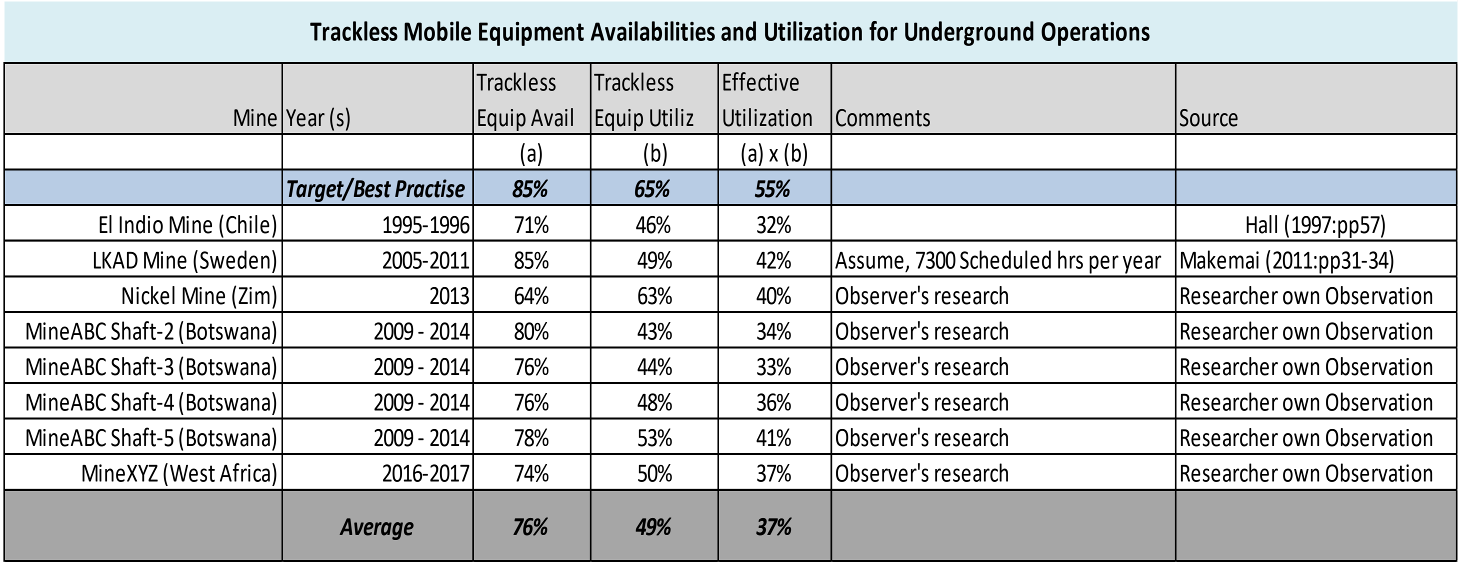
Even the long-term outlook for global metal prices and other energy commodities does not predict an immediate upturn to the prices maybe until 2020. This situation requires businesses to be innovative if they are to survive. Only highly efficient and low-cost producers are likely to be the ones to survive. The situation of low commodity prices is becoming the new normal.

1.2.6. Context – Low underground trackless equipment utilization

For mechanized operations, effective utilization of trackless mobile equipment is one key metric with a strong bearing on production throughput. Trackless mobile plant comprises specifically rubber tyred mobile hydraulic drill rigs, roof support bolters, load haul dumpers (LHDs) and dump-trucks as key production equipment.

From the researcher's own experience at MineABC and Mine XYZ, the industry norm or best practice normally sets diesel trackless plant availability at 85% and utilization at around 65%. This gives an Effective Equipment Utilization(EEU) of 55%. Durrant-Whyte, et al., (2015) show that the overall equipment effectiveness (OEE) in underground mining equipment is only at 29%. EEU is a measure of the actual equipment time used effectively in producing the required product quantity and OEE includes the quality loss factors.

Therefore for EEU of 55% in a shift of 10 hours, it is expected that the plant operates 5.5 hours doing productive work. In practice, it is always a big challenge in non-autonomous mining situations to attain an EEU of 55%. Observations by the researcher as well as a literature scan (Hall, 1997; Makemai, 2011) of underground mechanized and semi-mechanized shafts/mines operating trackless equipment reveals the following scenarios indicated in Table 1.1:



Trackless Mobile Equipment Availabilities and Utilization for Underground Operations

Mine	Year (s)	Trackless Equip Avail	Trackless Equip Utiliz	Effective Utilization	Comments	Source
		(a)	(b)	(a) x (b)		
	Target/Best Practise	***85%***	***65%***	***55%***		
El Indio Mine (Chile)	1995-1996	71%	46%	32%		Hall (1997:pp57)
LKAD Mine (Sweden)	2005-2011	85%	49%	42%	Assume, 7300 Scheduled hrs per year	Makemai (2011:pp31-34)
Nickel Mine (Zim)	2013	64%	63%	40%	Observer's research	Researcher own Observation
MineABC Shaft-2 (Botswana)	2009 - 2014	80%	43%	34%	Observer's research	Researcher own Observation
MineABC Shaft-3 (Botswana)	2009 - 2014	76%	44%	33%	Observer's research	Researcher own Observation
MineABC Shaft-4 (Botswana)	2009 - 2014	76%	48%	36%	Observer's research	Researcher own Observation
MineABC Shaft-5 (Botswana)	2009 - 2014	78%	53%	41%	Observer's research	Researcher own Observation
MineXYZ (West Africa)	2016-2017	74%	50%	37%	Observer's research	Researcher own Observation
	Average	***76%***	***49%***	***37%***		

Table 1.1 – Underground Trackless Equipment Effective Utilization

The effective utilization time averages only 37% with the highest among these mines only being 42%. There appears therefore to be a lot of structural challenges which underground mines face to be able to effectively utilize the available plant capacity. A survey of these mines show that most of the issues or delays which impact on effective use of the mobile plant include:

- Engineering related delays - which can account for between 15% in best cases and 35% in extreme cases. These delays include breakdowns, planned maintenance, response delays, logistical delays including waiting and collecting tools and spares.

- Poor breakdown and emergency response - A situation at ***MineABC*** , a copper nickel mine under study, showed that the actual artisan repair time is 50% of the total breakdown time, the rest of the time is made up of delays in calling the artisan and the time the artisan takes to organize tools, spares and travelling to the breakdown place(MineABC reports, 2015). Hedding (2014) explains that effective wrench time (actual on the job repair time) for most maintenance teams is between 25% and 35% of the artisan's total time and while world class target pegs wrench time at 65%. A lot of time for technicians or mechanics is wasted in activities such as travel, administrative, waiting for instruction, tools, collecting spares, etc.

- From the mines observed by the researcher, operational and mining delays can contribute the greater part of the system delays and these normally happen as start of shift delays (SOS), end of shift (EOS) and operational (OP) delays during mining processes. The author's experience shows that even though equipment may be available, it is rarely utilized beyond 50% of the available time in most underground mines and the best case is when the plant was utilized 50% of the time. Some machines like drill rigs can be utilized as low as 20% of the available time.

The hypothesis therefore is that the low effective utilization of trackless mobile equipment in underground mines could be improved if these activities and delays are made visible to management and critical decision makers quicker and preferably in real-time.

1.2.7. Context - Technology Constraints

Bandyopadhyay et al., (2010), NIOSH (2011), Song, et,al (2013) and others show that ccommunication infrastructure and configurations are still a major constraint to effective application of new technologies in mining processes. There are still a lot of challenges in developing technologies which can easily transmit voice, data and picture/video to and from underground to ensure real-time control of underground mining activities (Bandyopadhyay et al., 2010), NIOSH, 2011, Becker, 2014).

Equally important is that most of the actual mining processes are batch process and thus challenges associated with control of batch systems are always inherent in the mining process.

1.3. RESEARCH HYPOTHESIS

This research was based on the hypothesis that there are opportunities in trackless underground mines to improve production throughputs through better data driven decision-making systems. This is more so in developing countries which could still be lagging in terms of technology and systems to support better operational decision making, thus constraining available mine capacities.

There is a therefore a legitimate need for underground mines to look at improved decision-making systems for enhancing right and prompt decisions which can increase mine production capacity and thus unlocking greater potential for sustainability.

This hypothesis was motivated by years of observations from the researcher during employment in different mining operations in Africa. To test this hypothesis, the study was to address three key objectives as discussed below.

1.4. OBJECTIVES OF STUDY

The main purpose of the study was to identify opportunities for maximizing mining output through improved data driven production decision-making systems in underground hard rock trackless mining operations. The approach to the study was to use available historical production data and business records in selected mines and perform detailed technical and statistical analysis based on the production equation (1.1), being :

$$\text{Production volume (tons)} = \text{production rate (tons/h)} \times \text{total operating hours (h)} \qquad (1.1)$$

The main goal of the research was thus to be achieved through the following three sub-objectives linked to the equation of production (1.1):

(1) To analyse key technical factors that impact ***production throughput rates*** in a trackless mining production system and propose improved decision-making criteria.

(2) To identify major operational activities which impact on ***effective mining operating times*** and how this can be improved through better visibility and decision support systems*(DSS)*.

(3) To illustrate how a ***decision support system (DSS) architecture*** can be configured for improving decision support.

1.5. SCOPE AND APPROACH

Various non-experimental research methods were used involving direct observations by the researcher at the different work places, studying of archived business documents, interviews, brainstorming sessions and on-line surveys in a case study approach were employed to collect data.

After data collection, different analysis methods were used to analyse the data and develop critical correlations between mine throughputs and variables such as reliability, maintainability, capacity and operating environments. An important approach used was to take a mine production system as a quasi-manufacturing system so that the mathematical models that describes the dynamics of production processes at both system and equipment levels can be applied. Equipment performance data using serial and parallel production system models was applied and then analyzing decision criteria which enable operational effectiveness of such models.

Generic system engineering and lean-sigma tools were also found useful in identifying the context, analysis of system functions and activities (functional analysis) and coming up with value maps which help to identify system bottlenecks to throughputs.

Due to the broadness of the subject, time and resource limitations, it was not possible to do a full industry wide survey on the application of decision support technologies in underground mining, but phases of preliminary system design and system specification were done without going into detailed/component design of a system. No preferred technology was to be chosen and no carrying out of trade off studies was to be done in the study.

1.6. EXPECTED BENEFITS

The research was expected to demonstrate that underground mines in developing economies can increase their productivity and mining throughputs by improving their decision-making systems using detailed data analysis methods. There are also benefits which can be derived by taking advantage of the new technologies in the market with appropriate investments in the right systems and changing paradigms. The research also sought to contribute further knowledge regarding the development of generic frameworks for improved decision-making systems through throughput analysis for underground hard rock mines. This is an area that could still need to be fully exploited.

2. REVIEW OF LITERATURE

2.1. CHAPTER OVERVIEW

This chapter reviews literature available on how improved decision making paradigms can impact mining throughputs in underground trackless production systems. The focus was with the specific emphasis on factors which have influences on production rates, availability, reliability, maintainability and utilization of underground mining systems.

No paper could be identified by the researcher with direct mathematical models which describe the dynamics of production rates and throughputs in underground trackless mining systems. However, several writers have discussed the issues of system throughputs in generic manufacturing facilities and the following are the some of the widely quoted in this report; Alden, et al., (2006), Blumenfeld & Li (2005), Li, et al., (2009), Barabadi, et al. (2011) and Gharahasanlou, et al., (2016). Also a lot of information on dynamics of stocks, flows and delays in production system was of key importance from the work by Sterman(2000).

Therefore an approach used in this research in studying the mining production system is to assume and model a mining production system as a typical parallel/serial manufacturing facility. This enables theoretical models that govern typical manufacturing production processes to be applied in a minig system. The chapter is thus organized as follows

2.2. STOCKS AND MATERIAL DELAYS IN PRODUCTION SYSTEMS

Stocks are accumulations of materials in manufacturing and production systems. Sterman (2000) explains that stocks give system inertia, creates delays by accumulating the difference between the inflow to a process and its outflow. He also alludes that by de-coupling rates of flows, stocks are the source of disequilibrium dynamics in systems and thus a failure to understand the difference between stocks in a system and flows leads to underestimation of the causes of delays in the system and creating a short-term focus (Sterman, 2000).

The general structure of stocks and flow is represented by Figure 2.1. The valve represents a flow regulator and the clouds represents the stock of raw materials before the process and after the process is the stock of product, which are assumed to be infinity sources and sinks of the system and never constraints the system.

Figure 2.1 – General structure of stocks and flows in dynamic systems (Source, Sterman (2000))

Assuming infinity sources and sinks, stocks are the result of the difference between the inflow and the outflow. In a mathematical format, the stocks accumulate or integrate the flows and the net flow into the stock is the rate of change of the stock (Sterman, 2000). Equation (2.1) will thus represent the Stock, represented by S(t)

$$\textbf{Stock, S(t)} \quad = \quad \int_{to}^{t}[\boldsymbol{Inflow}(\boldsymbol{s}) - \boldsymbol{Outflow}\ (\boldsymbol{s})]\boldsymbol{ds} \ + \boldsymbol{Stock}(\boldsymbol{to}) \qquad (2.1)$$

Where Inflow(s) represents the value of the inflow at any time s between the initial time t_o and the current time *t*. Equivalently, the net rate of change of any stock, its derivative, is the infow less the outflow, defining the differential equation (2.2).

$$\textbf{d [S(t)]/dt} \quad = \quad \textbf{Net Change in Stock} \quad = \textbf{Inflow(t) – Outflow (t)} \qquad (2.2)$$

In a manufacturing system, the flows are represented by the throughputs, and the stocks by buffers in the system. For an underground mining production system, the inflows can be represented by the blasted rocks and the outflow can be represented by the hoisted tons, and the stocks by draw points and silos underground. In general the inflows will be functions of the stock and other state variables and parameters.

One of the most important outcomes of understanding the dynamics of flows is to be able to determine the delays in the system. A delay is a process whose output lags behind its input in some fashion (Sterman, 2000) as shown in Figure 2.2.

Figure 2.2 – General structure of a Delay in a system (Source, Sterman (2000))

In a case of physical flow of materials, the delay represents a material delay which is a representation of the Material in Transit (MIT) or Work in Process (WIP). If D represents the average delay time or residence time of the WIP stock in the system, The general structure of a material delay system is shown in Figure 2.3.

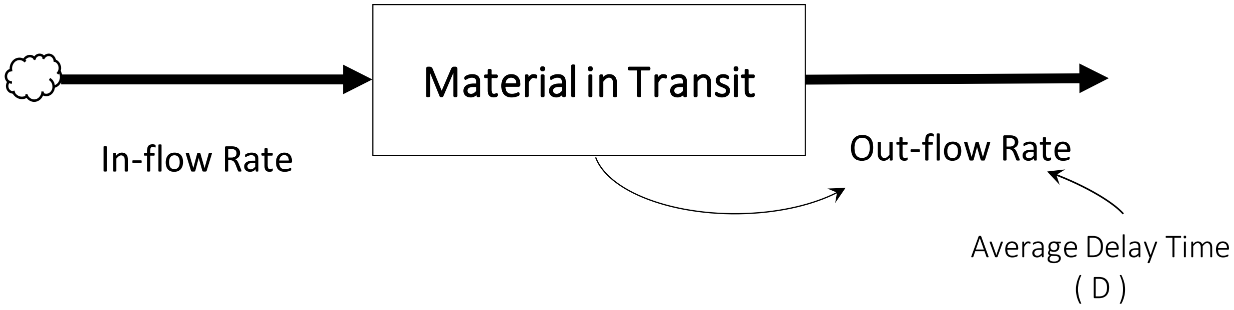


Figure 2.3 – General structure of Material in Transit (Source, Sterman (2000))

Sterman (2000) gives the outflow rate of a delay system with an average Delay time D, by equation (2.3) :

Outflow = Material in Transit / Average Delay Time = S(t)/D (2.3)

or, **Average Delay Time (D) = Material in Transit / Outflow** (2.4)

The equations (2.3) and (2.4) are very useful for estimating the delays and flow-rates of products out of a production system. Figure 2.2, and 2.3 represents a pipeline and first order delay system where there is only an input and output in single stage with perfect mixing or a simple first in first out (FIFO) process. However, in real practice, say in a mining process with different stages of the process, a process has many stages and different first-order stages may be cascading from one to the next. Figure 2.4 represents a structure of a two stage higher order delay system.

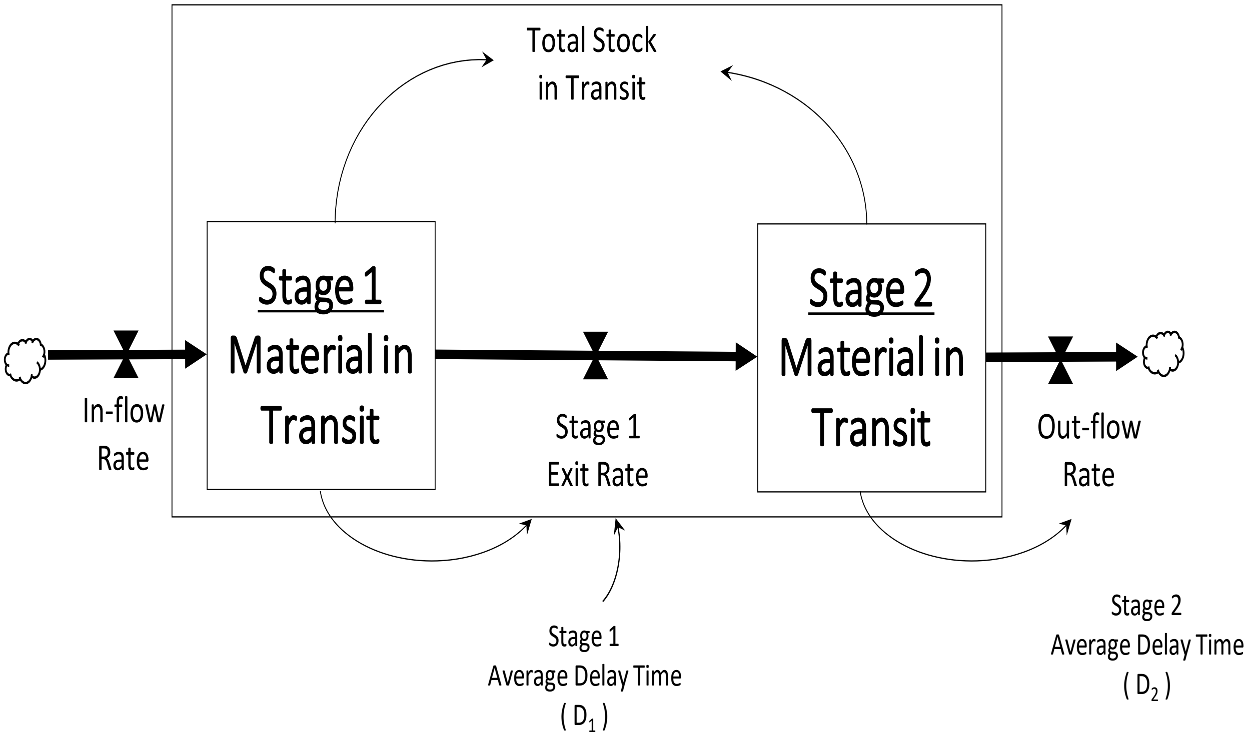


Figure 2.4 – General structure of higher order Material in Transit (Source, Sterman (2000))

In many practical situations, the total stock of a multi-stage system is found by the sum of the stock in each transition stage of a higher order system, and the average total delay from inflow to outflow is the sum of the average delays of the individual stages *(Sterman, 2000))*. This notion can be very useful in developing of value stream maps and load balancing of a production facility.

2.3. DECISION FACTORS WHICH IMPACT PRODUCTION OUTPUT CAPACITY

System throughput capacity is an important measure of performance for a production line and can be measured as the physical output per unit time produced by a system or sub-system in a production facility (Barabadi, et al.,2011). In mining it can be calculated as tonnage of rock that can be extracted or moved per unit time. Example will be the number of loads of ore moved per hour by a loader or a truck.

Barabadi, et al., (2011) also shows that prediction and analysis of system throughput capacity for a production facility is a very important factor in decision making for managers and engineers. He alludes that it is useful and necessary in both engineering design and optimization during the operation phase of the mine equipment, as well as providing information that is essential in purchasing of a system and establishing of maintenance schedules.

Due to the randomness in production (machine breakdowns, random processing times, etc.), the quantity of output produced by a production system is a random variable (Alden, et al., 2006; Blumenfeld & Li, 2005). Various analytical and process models have been developed to analyze throughput and identify bottlenecks for production lines in manufacturing industries.

These analyses normally focus on a serial production line comprising work stations separated by buffers and Aldien's method is one of the popular methods used (Alden, et al., 2006; Blumenfeld & Li, 2005). Also, these models assume that the stations are subject to random failures. The throughput of such a production line depends on each station's speed (processing rate) and reliability, and the sizes of the buffers.

Alden, et al. (2006) shows that serial production lines are the most practical in many manufacturing organizations and form the backbone of many main production systems. In its simplest form, a serial production line is a series of stations separated by buffers as shown in Figure 2.5, through which parts move sequentially until they exit the system as completed jobs (Alden, et al., 2006).

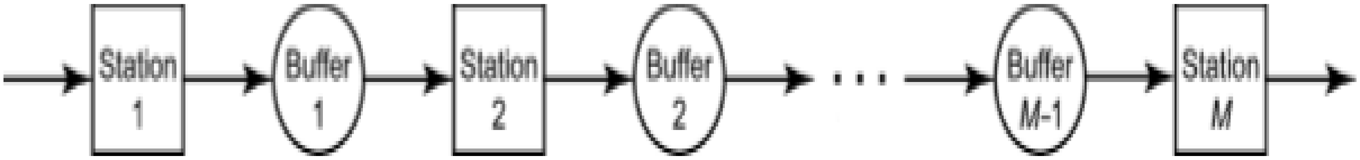


Figure 1: A simple serial (or tandem) production line is a series of stations separated by buffers. Each unprocessed job enters Station 1 for processing during its work cycle. When the work is complete, each job goes into Buffer 1 to wait for Station 2, and it continues moving downstream until it exits Station *M*. The many descriptors of such lines include station speed, station reliability, buffer capacity, and scrap rates.

Figure 2.5 – Representation of a serial production system (adopted from Alden, et al., (2006))

Alden, et al., (2006), Blumenfeld & Li (2005), Li, et al., (2009), show that exact mathematical solutions for system throughput can only be derived in two-machine line models. For systems with more machines, approximate solutions are normally used mostly based on either aggregation or on decomposition approaches. Underground trackless mining production approaches more a parallel production system (Li, et al., 2009). Parallel systems have more machines of same type in a work station and have an advantage that they can be used to increase the production capacity.

Most analyses study parallel lines by equivalence, i.e. aggregating parallel machines into an equivalent single machine as illustrated in Figure 2.6 adopted from Li, et al., (2009). In underground mining, the different production stations may involve number of drill rigs, underground loaders (LHDs), trucks, etc. and these can be aggregated into single line equivalent machines.

The intermediate buffers include draw-points after blast, temporary muck piles, ore and crusher tips and underground and surface silos. It therefore can be assumed that an underground trackless mining system be represented as a parallel distributed production system with the following configuration as presented by Figure 2.6.

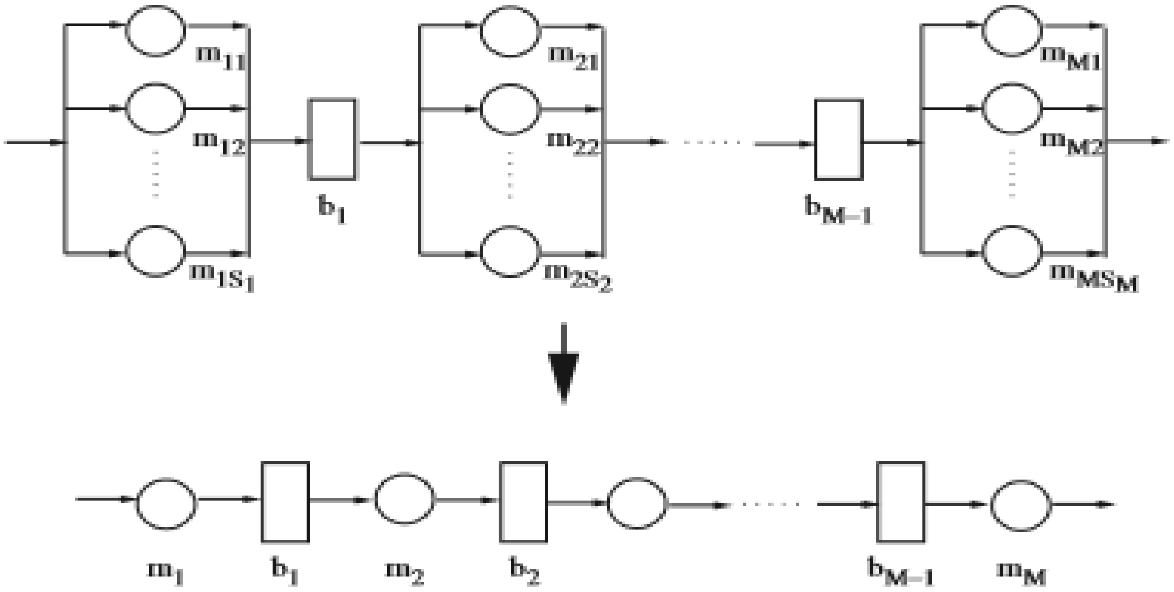


Figure 2.6 – representation of a parallel production system (adopted from Li, et al., (2009))

Impact on production throughput is not only a factor of the capacity of the equipment used. The capacity of the system components (or equipment) need to be taken in relation to the environment in which they operate. Therefore, this Chapter also covers at the system level issues which impact on throughput such as flow of data and information to make right decisions.

Many authors have discussed the issue of system throughput for a generalized serial production system but very few authors were identified who dealt with detailed throughput analysis in an underground mining environment. However, articles by Barabadi, et al. (2011) and Gharahasanlou, et al., (2016) which dealt with throughput analysis for surface mining were useful and contained information referred to and used in this research.

Barabadi, et al. (2011) shows that throughput capacity in a mine is affected in a complex way by such factors as equipment reliability, maintainability and capacity of the equipment, which form components of the production system. These in turn are affected by system level factors such as the operational environment on which these components operate (heat, water, rock type, etc.), skills of operators, maintenance policy, logistical support, etc. (Barabadi, et al., 2011).

It is therefore important when doing a production analysis of a mining operation to consider these factors. The overall throughput capacity of the mining system will not depend on the throughput capacity of its components only, but also on the way these are interconnected to form the overall system.

It was therefore crucial when carrying out a throughput analysis in this research for the analysis to be considered in two phases to account for the above factors by, (1) calculating the component characteristics of reliability, maintainability and capacity, and then (2) building a model at system level that represents the relationship between components and their interactions with environment and other systems.

Barabadi, et al. (2011) also allude that increasing mechanization and automation in mining has resulted in mining equipment becoming more complex and sophisticated and its cost is increasing. In an underground mining, there are many factors which affect the performance of the equipment such as the production plan, underground environment conditions, maintenance, the equipment operators, etc.

Environmental factors such as dust, temperatures, heat, water, roadway conditions, rock type, rock strength, etc. affect the human performance (operators and operating crews) as well as the mining equipment (Barabadi, et al., 2011). Mining equipment performance such as reliability, maintainability and capacity are all affected by environmental conditions such as temperature, heat, water, roadway conditions, lighting, etc., causing unpredictable failures of components and machine systems (Barabadi, et al., 2011).

2.4. SYSTEM VALUE CONSIDERATIONS AND PROJECT JUSTIFICATIONS

In mining operations, it is important that right decisions are made at the right time due to the high safety and economic risks inherent when wrong decisions are made. There are usually large costs to pay and life may be lost if something goes wrong underground due to the complex geographical configurations, which requires systems that support prompt decision making and action.

In many cases, new technology may be required to aid in improving the decision making for a production system. This may involve investments in new technology. However, many authors in the past have argued that justifying the implementation of a new technology is a more complex process which fails to meet most of the economic justification criteria such as payback or IRR resulting in the projects being abandoned (Troxler & Blank, 1990).

Authors such as West & Randhawa (1990), Soni, et al, (1990) and Troxler & Blank (1990) argue that evaluation and justification of new and advanced manufacturing systems require also detailed consideration of other non-economic strategic issues such as improved quality, productivity, flexibility, equipment and plant modernization strategies, and the impact on total system value.

Troxler & Blank (1990) point out the importance to present a justification that has an impact on the overall enterprise system value, rather than on a few elements of it. Besides the financial benefits and corporate strategy issues, three areas which impact total system value are:

1) System Capability Factors such as system design, function, reliability, availability, flexibility and human factors.
2) System performance factors and indicators such as system throughput – cycle time and lead time, quality, inventory, information flow and relevance, and capacity utilization.
3) System productivity factors and indicators – such as price and volumes, cost of capital, capital equipment, engineering costs, materials, energy and facilities.

Any investment in technology must be able to increase an enterprise value through impacting the above. Figure 2.7 indicates areas where opportunities for improved decision support technologies can impact system performance.

2.5. CONVENTIONAL OPERATIONAL DECISION-MAKING CHALLENGES

In most traditional underground mining systems, especially in developing countries, the information system is still manual, spreadsheets and paperwork based. This makes it difficult for fast flow of information to aid decision making. A mine decision system, like any manufacturing system, must consist of the physical system and an information system both of which are planned and controlled by a hierarchical decision architecture (Rembold, et al.,1993).

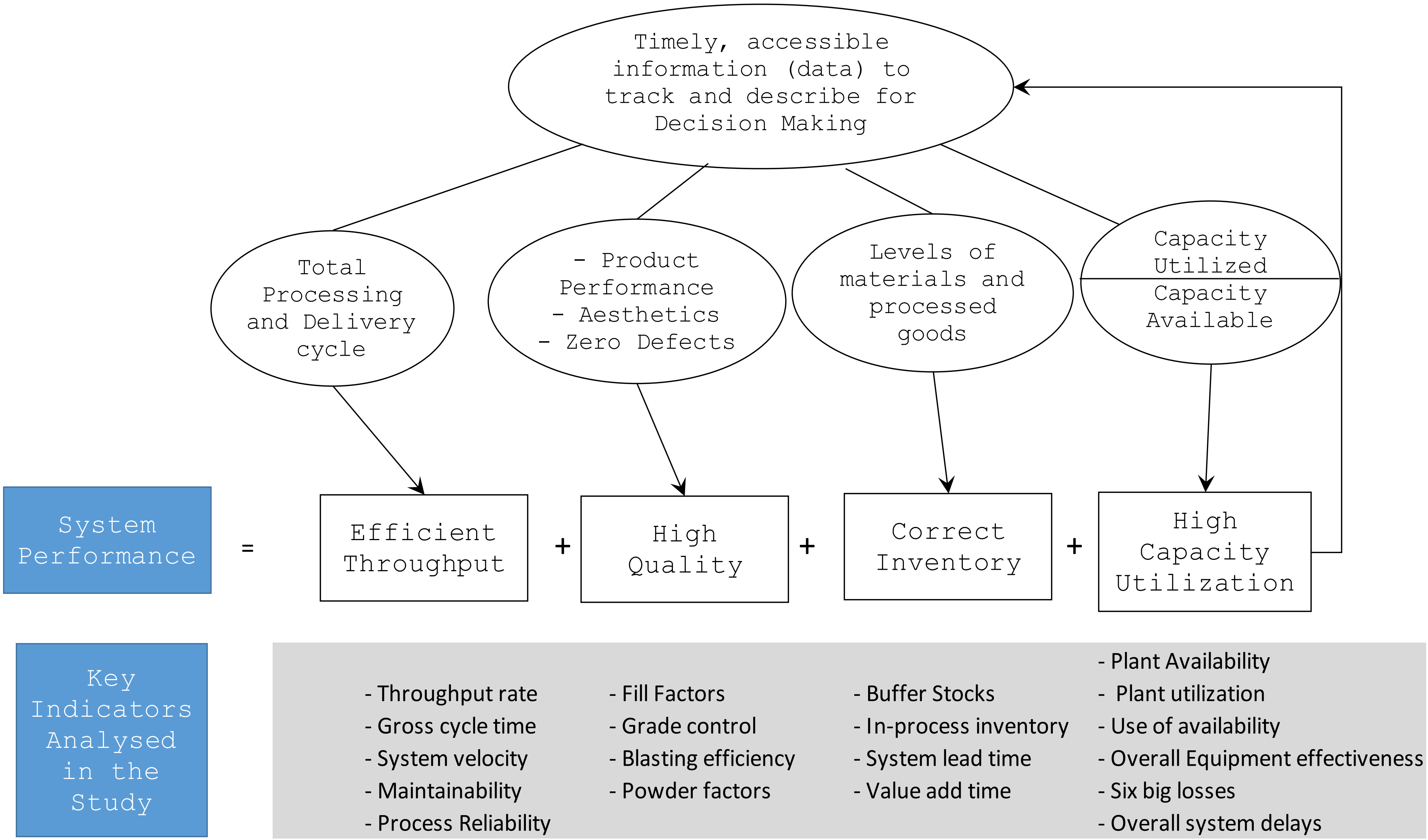


Figure 2.7 – Areas that affect overall production system performance (Source- Troxler & Blank, 1990)

Most of the older mines' operational systems require operators, shift bosses, mine-captains, artisans/mechanics, engineering foremen and supervisors to fill in operating data on manual sheets which are then collected and submitted at the end of the shifts. An operational or engineering clerk is then used to capture this information in a spreadsheet or an ERP system and then produce shift or day reports at the end of the shift or in most situations the next morning. Most decisions made in the mine are made independently of all the other concurrent activities as they are normally not visible to the decision maker during the shift time because of geographical barriers.

It is not always possible and not easy in underground mining for supervisors to have knowledge on the state of things all the time as the systems are specially distributed and not easily visible. Sage and Armstrong Jr. (2000), and Lifson (1972) show that in many situations information is always incomplete when a decision needs to be made, thereby introducing uncertainty and inefficiencies in the outcomes of the decisions. It is thus important that the right key performance indicators (KPI) are made visible to the decision maker for each value parameter whenever making decisions.

A report by Hall (1996) from AMC Mining Consultants illustrates a typical traditional mine operational and information system scenario and the dangers associated with such a situation, quoted below:

> Common comments found in most traditional mines as quoted from Hall (1996)
>
> *"1. People record what is convenient for them - "At present we only seem to record what makes the person or section doing the recording look best."*
> *2. No agreement on what the correct fact of events for the day is - "I once saw a situation where operating and maintenance supervisors were not allowed out of the mine until they agreed upon the times that broken-down equipment became available again. In retrospect, it might have been better to let the records show simultaneous "down" and "up" time, to highlight the severity of a communication problem which needed addressing."*
> *3. No single source of Truth - The above identifies two problems:*
> *1. Ensuring information is recorded correctly, to engender confidence in the base data for all subsequent reporting and decision making.*
> *2. Ensuring that all relevant data is gathered. A half-truth is often as bad as an outright lie. Similarly, incomplete records can be misleading, with potentially serious consequences.*

> *4. Analysis of Data to useful information - These lead on to two further issues:*
>
> *1. Adequately summarizing the data to create useful information – our computer power is such that there is no excuse not to do this these days.*
>
> *2. Ensuring that the statistics generated are properly understood, especially about what is good, satisfactory, or poor, both for individual measures and for relationships between them.*
>
> *5. Some great dangers from wrong information*
>
> *1. Availability and Utilization Statistics Misapplied – required available hours not provided, excessive available hours, wrong statistic for business decision, etc.*
>
> *2. Unit costs variances not proving anything – what actually drives the costs is not known.*
>
> *6. Believable schedules – schedules not achieved because they don't take care of the constraints – ventilations, compressed air, power, roadways, etc."*
>
> *Texts Quoted from Hall, AMC Consultants* (Hall, 1996)

The above quote shows that in typical traditional mines, control information is difficult to receive at higher levels in the shortest possible time or in real-time due to the need to manually process large quantity of data from the lower levels and congregate it into useful decision-making information (Rembold, et al.,1993). As information goes up the ladder, feedback time for control data increases causing delays for higher level management to make corrective decisions (Rembold, et al.,1993).

2.6. IMPORTANCE OF DECISION SUPPORT SYSTEMS IN UNDERGROUND

Decision making in underground systems involves making decisions on many interacting resources or elements in the form of human beings, geo-technical conditions, materials, complex equipment and mining systems, software, facilities, data and information (Blanchard, 1991) in a short time period. The interaction of these different elements needs to be coordinated appropriately for the expected goal to be achieved in changing and dynamic environment (Lifson, 1972).

Because of the complexity, the human decision maker may not be able to comprehend and make appropriate decisions that support business goals, especially where there are definite information gaps to inform the decision-making process (Blanchard, 1991; Silver,2008). It is therefore very important to have systems in place to aid in decision making. Decision support systems (DSS) are systems, processes and technologies that are put in place to support better decision making (Silver,2008; Stein, 2011). They assist the decision maker to understand the problem before them and to formulate a knowledge-based solution (Silver,2008; Stein, 2011; French, et al., 2009).

Neiger & Churilov (2008) highlight that the concept of decision support systems (DSS) has become of more importance in the success of many organizations to support the limitations in human decision making. DSS concerns processes and technologies that support better decision making in organizations and complex systems through facilitating better execution of business processes and to minimize costs while maximizing returns and value (Neiger & Churilov, 2008).

In underground mining, availability of information and/or knowledge on what alternatives to take may be limited due to the difficulty in accessing information in time (Sage & Armstrong Jr. 2000, Lifson,1972). This makes the human capability limited in terms of decision making. DSS helps to assist the judgement capability of the human in making better and informed choices.

Emergency situations like machine or process breakdowns, serious accidents, collapse of roof structures, flooding of mines, fires, gas explosions, etc. always demand decisive decisions to be made quickly in short time spans (Van de Walle and Turoff, 2008). These decisions are also affected by the geographical/spatial distribution, the choice of "where" is an important part of deciding "how" to handle the situation (Keenan, 2008).

Physical barriers underground make it even more difficult to make appropriate supervisory decisions due to visibility challenges of the operations. Underground mechanized mining systems are highly distributed and use of geographical information systems (GIS) can facilitate the organization and display of spatial data and provide a variety of distinctive spatial operations with that data (Burstein, et al., 2008; Keenan, 2008).

Burstein, et al., (2008) say that to support decision making in real-time, the role of mobile technology is increasingly evolving in conjunction with wireless networking capabilities. These advances in wireless and mobile technology bring in new opportunities for real-time and on-the-spot decision making with potential to save time and increase productivity (Burstein, et al., 2008).

Decisions made at each stage of the mining operation are responsible for controlling the flow of information and resources and in turn impact the throughput. The impact of each decision made depends on the tier in the organization at which it is being made (Rembold, et al.,1993). Decision structures in enterprises are normally laid out in pyramid forms and decision making is divided into four distinctive layers as strategic at the top, tactical planning, operational control and machine control (French, et al., 2009; Rembold, et al, 1993).

The importance of decisions increases up the pyramid with consequences of decisions being more significant, while frequency of decisions increases towards the base as shown in Figure 2.8.

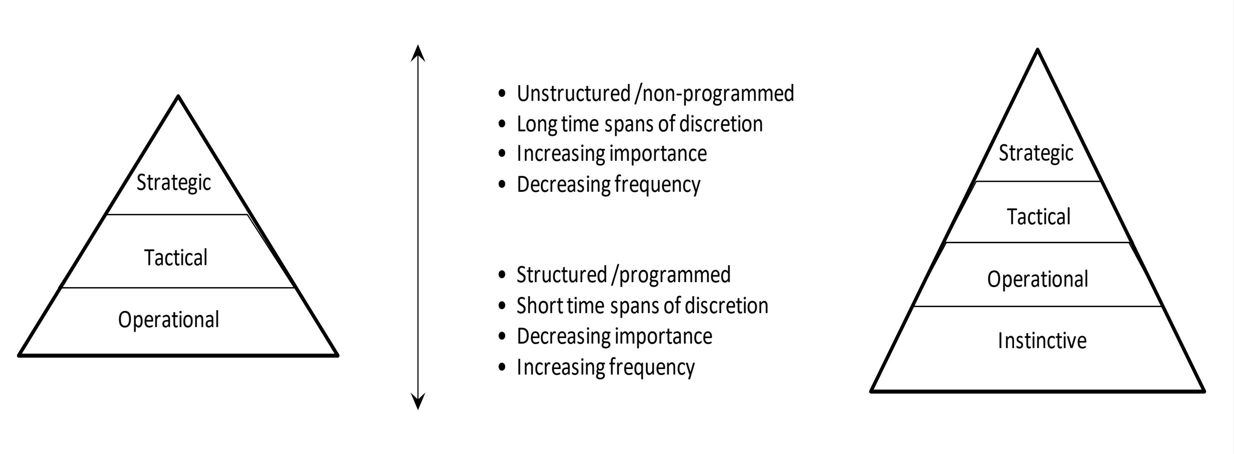


Figure 2.8 – Organizational decision making pyramid (adopted from French*, et al*., 2009)

Rembold, et al., (1993) explains that at lower levels, many control decisions are made in parallel, but these have minimal impact to the entire system but will have more localized impact. These decisions must be made quicker and data must be converted quickly into information as it goes up the ladder to allow corrective decisions to be made at each tier up the ladder, which is not practical to achieve using manual coding systems (Rembold, et al.,1993).

An improved decision system for a mining system must be able to operate in real-time so that fast decisions can be made. Right information and plant status must be available to each key decision maker at the right time. This includes the human-machine interface at the operator level to intelligent analytics at the executive levels, through an appropriate decision support system.

French, et al., (2009) define four levels of decision support. The first level, level 0, refers simply to presentation of data with the DSS simply extracting the relevant data from the databases and presenting it with minimal analysis. This includes Management Information Systems (MIS) and Executive Information Systems(EIS). However at the highest level, Level 3, is an intelligent system which provides prescriptive support through helping decision makers weigh conflicting criteria and also balancing potential benefits and costs with key uncertainties (French, et al., 2009). Table 2.1 summarizes these features of a DSS.

Levels of decision support

Level 0	Acquisition, checking and presentation of data, directly or with minimal analysis, to Decision Maker
Level 1	Analysis and forecasting of the current and future environment
Level 2	Simulation and analysis of the consequences of potential strategies; determination of their feasibility and quantification of their benefits and disadvantages.
Level 3	Evaluation and ranking of alternative strategies in the face of uncertainty by balancing their respective benefits and disadvantages

Table 2.1 – Levels of decision support (adopted from French, *et al*., 2009)

In a mechanized mining operation, trackless equipment is used for the mining operations. This includes diesel and electro-hydraulic powered self-propelled mobile equipment such drill rigs, loaders, trucks and various support equipment. These machines always work in various distributed places in the mine and can be made to capture all their operating data which can be extracted at the right time to aid in decision making.

Most modern trackless machine systems can extract data showing the machine health in real-time which can aid the operator, operational supervisor and maintenance personnel to make quick and right decisions using mobile equipment monitors. Many technology providers have new systems which provide remote access to equipment operating data over the mine’s wireless networks and provide visibility and analysis of equipment performance (Atlas Copco, 2017; Sandvik, 2016; Caterpillar, 2017; ABB, 2017; Honeywell, 2017; Modularmining, 2017).

The important capabilities of most of these systems include provision of the following:

> *"Real-time fault notifications, Events-by-location on the tracking map, Data snapshots for root-cause analysis, Fault-specific diagnostic details, Historical notification trends, standard or user-defined dashboards, real-time displays, user-defined key performance indicators (KPIs),OEM-defined alarm and events, user-defined alarms and events, Predictive models for early identification of developing faults, Onboard systems such as tire monitoring, fuel and lube systems, merging real-time operating data with maintenance management, dispatch, financial and other systems for complete view of overall equipment effectiveness."*
> *[sources: websites, Atlas Copco (2017), Sandvik (2016), Caterpillar (2017), ABB (2017), Honeywell (2017), Modularmining (2017)]*

Some of the key health status checks done on equipment from improved systems include

> *"Machine Health Monitoring, Temperature Loss Monitoring, Temperature Rise Monitoring, Fluid Coolant Flow Detection, Fluid Coolant Leak Detection, Mechanical Noise Detection, Bearing Wear, Mechanical Insertion Detection, Audible Noise Detection, Slope change detection, Vibration detection"*
>
> *[sources: websites, Atlas Copco (2017), Sandvik (2016), Caterpillar (2017), ABB (2017), Honeywell (2017), Modularmining (2017)]*

2.7. INTEGRATED MINING FOR IMPROVED OPERATIONS VISIBILITY

Another very important element which impact mining production throughput is through improved production planning and control. This area has been studied in various papers available for general production systems (Li, et al., 2009). Very limited information could be identified in terms of scientific research specifically related to optimization models for underground operations. However, considerable technical and commercial information is now available from equipment manufacturers, mine planning software developers, reports on mine-planning systems and mining magazines and journals. Various technologies and systems available for underground mining which do support improved decision making have been described.

Technologies available now are pushing towards integrated mining systems and use of real-time decision support systems as value adding factors. This concept is seen to being progressed and implemented most from about five frontiers as follows, namely; (1) mine planning and scheduling software developers, (2) fleet management and dispatch software systems, (3) mining equipment original manufacturers (OEMs), (4) process automation companies, and (5) underground mining communication infrastructure developers.

The details on the technologies available for integrated mining and automation are beyond the objectives of this research study but information is readily available on the websites of these companies. However, what is of interest to this report is how the use of data, information analytics and integrated systems are expected to impact on mine throughputs. Technical reports and marketing documents from the manufacturers shed a lot of light on these technologies, although there is need to provide real proof of the benefits.

The focus on most of the new technologies is on increasing mine visibility to improve control. Some of the new technologies come with advanced analytical capabilities to aid in better decision making.

One of the key and fundamental developments in integrated mining systems is the development of a mine operations centre, as represented by Figure 2.9. The mine operations centre is expected to provide a real-time visibility of mining operations to the critical decision makers in real-time and appropriate decisions on system and equipment level throughputs, cycle times, breakdowns, machine health status and mean-time to failures are made in time to control variability in the production system (Westerlund & Sanchez, 2015).

Figure 2.9 - Concept of mines operations centre and ore factory (Westerlund & Sanchez (2015))

Some of the benefits of a mines operations control centre are as described by Westerlund & Sanchez (2015) and ABB (2017) are: providing an integrated Mines Operations Control centre for production and fleet management, energy and asset management, asset and personnel tracking, process control and tele-remote, increasing the situation awareness by enabling real-time positioning and information of vehicles, equipment and personnel together with visualization in 3D maps, increase the level of automation by providing control system with real-time location information for position based ventilation control, traffic control, etc., take better decisions for dispatching, traffic management and production control, and improve collaboration between personnel in underground mines by integrating voice, messages and CCTV services from the 3D view of the mines.

Integrated mining system are taking advantage of the development of manufacturing execution systems (MES) in underground mining systems. MES integrate different systems such as mine planning, mine operations, short term scheduling systems, plant floor systems and general business enterprise resource planning system (ERP) such as SAP.

Meyer, et al. (2009), Hwaiyu (2004) and others describes an MES as systems which enable optimization of production activities using current and accurate data. MES guides, initiates, responds to and reports on plant activities as they occur and can provide facility wide execution of work instructions and information about critical production processes which can be used for many decision-making purposes. It provides a real-time view of the current situation of the plant-floor production. Figure 2.10 is an illustration of modern web based decision support architecture adopted from a geological mapping system by (Lin, et al., 2008).

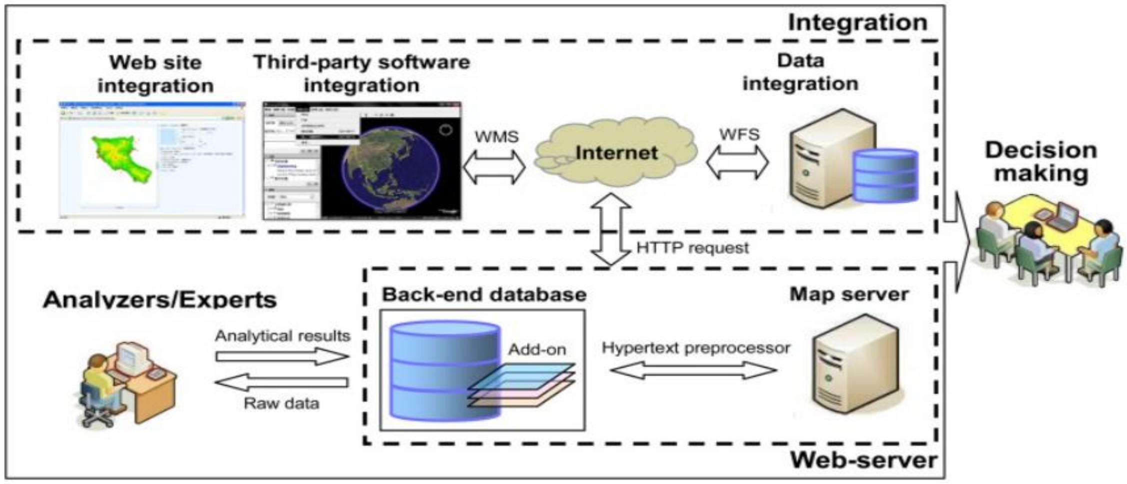


Figure 2.10 Concept of a modern integrated decision-making system (adopted from Lin, et al., (2008))

A slight extension of the short-term mine scheduler software is the Computer Aided Dispatch (CAD) systems which are used for supervisory fleet management. These have also been developed for underground mining systems to bridge the gap between trackless equipment used in mining and the ERP and they are expected to provide "as an end-to-end solution" for underground mining systems (Mining magazine, May 2016; ModularMining, 2017)

2.8. IMPROVED UNDERGROUND MINING COMMUNICATION ARCHITECTURE

The main challenges in developing advanced systems underground have been the limitations in underground communications infrastructures which can transmit voice, data and video from underground. However, development has taken place from communications companies to bridge this gap (Bandyopadhyay et al, 2010; Song, et al, 2013; Australia NIOSH-Mining Division, 2014).

Communication systems are key in the actual implementation of any real-time decision support system because they provide the backbone upon which actual automation of underground is based. Various companies are involved in the development of communication networks for underground which has been one of the biggest missing links in automation of underground operations.

Major companies like Becker mining systems (2017), Laird Technologies (2017), etc., show that they provide smart communications platforms for underground mining which can be used to integrate all the mining systems with technologies such as leaky feeder systems, voice and data networks, radio network systems, microwave links, and Wi-Fi solutions. The issue of underground communication infrastructure has been the biggest impediment in the development of appropriate technologies which support advanced decision systems.

2.9. STATISTICAL ANALYSIS AND ELEMENTS OF MODEL DESIGNS

Since the research was a non-experimental (correlational) study, it was hinged on analysis of large data to be used to make both deductive and inductive reasoning. This section gives a few key elements on statistical analysis of data applicable in the study. The information discussed in this section is quoted and derived mostly from the following authors: Oehlert (2010), Festing & Altman (2002), Seltman (2015), Nau (2014), uca.edupsychologyfilesChapt10 (2013), Hall (2018), Higgins (2005), Jain & Sing (2018), Prajneshu (2018), Kaluarachchi (2018)

(1) **Use of Preliminary Exploratory Analysis** – before doing any formal modelling, testing or estimation of data, it is required to carry out preliminary exploratory and/or graphical analysis of the data. Preliminary analysis normally includes: (a) Descriptive statistics such as means, medians, standard errors and interquartile range, and (b) Plots, such as stem and leaf diagrams, box-plots, and scatter-plots. These analysis reveals patterns in data and relative sizes of mean differences and experimental errors and gives much understanding of the data as any formal analysis procedure. Preliminary analysis can also be a great help in discovering unusual responses or problems in the data.

(2) **Statistical Models and Parameters** - A statistical model for data is a specification of the statistical distribution for the data (Oehlert, 2010). Models depends on parameters which influence the behavior of the model. The choice of model and parameter to describe statistical data is very key to describe the confidence level that can be put in the data. The main objectives in model analysis is deciding which model is the best description of the data, and making inferences about the parameters in the models.

(3) **Correlation and Regression** – Correlation and Regression are two important statistical methods which are used to compare the relationship between two variables. They are very useful in observational (also called correlation) study. Correlation is a process to establish whether a relationship exists between variables or not, but it does not imply causation or causal effect between the two variables. **A correlation coefficient** a number between -1 and +1 gives an idea of whether a relationship exists, and how good the relationship is between the variables under analysis.

On the other hand Regression Analysis is the art and science of fitting (mathematical) lines to patterns of data (Nau, 2014). It uses the existing data to define a mathematical relationship between the variables and which can be used to predict future values of data and can be extrapolated. Variables under analysis in statistics are classified as **independent** or **explanatory variable**, and **dependent** or **response/outcome variable.** Drawing of scatter plots is very fundamental to determining the relationships between the variables.

(4) **Critical statistical parameters in correlation and regression analysis** – the following statistical parameters are key in describing data and for evaluating the relationships between random variables which are useful in correlational research.

1- ***Characteristics of data*** – This is measured by central tendency (mean $\bar{U}$, median and mode),spread of data (variance σ^2 and standard deviations σ), **skewness** and **kurtosis**.

2- ***Coefficient of Correlation (r_{xy})*** – is used to express the strength of the relationship between variables and is normally represented by letter r_{xy}.

3- ***Coefficient of Determination (R^2***)- While the correlation coefficient only describes the strength of the relationship in terms of a carefully chosen adjective, the coefficient of determination gives the variability in dependent variable explained by the variability in Independent. The coefficient of determination is much more useful than the correlation coefficient in the sense that it gives a more plausible statistical explanation of the relationship between two variables X and Y. It is denoted by R^2 and is simply the square of the correlation coefficient. The Coefficient of Determination (R^2) tells the percent of variance in one variable that is accounted for by the other variable.

4- ***Significance levels*** - gives level of confidence in statistic outcome and hypothesis testing (through power, sample size and Type1 errors) - The significance level is the chance of obtaining a false positive result due to sampling error (known as a Type I error). It is usually set at 5% to give 95% confidence for most purposes, although lower levels are sometimes specified such as 1% for 99% confidence.

5- ***Non-Linear Regression*** – In practice, the relationship between the explanatory/independent variable (X) and the outcome variable (Y) is not always a linear relationship. Example of some very important non-linear functions includes the orthogonal polynomial to fit a polynomial of any order k in one variable, Cobb-Douglas Production Functions (hyperbolic, square root and exponential functions) and the Logistic function. Some nonlinear regression problems can be moved to a linear domain by a suitable transformation of the model formulation.

2.10. CHAPTER CONCLUSION

This chapter discussed critical methods and ways to analyse a production system. The approach proposed in this chapter was to model a trackless mining production system as a quasi-manufacturing system and use the general formulas that are used in estimating the dynamics of the system. This was so as there were few identified detailed models and research on the dynamic modelling of underground production systems that are published. The researcher couldn't find any such documents in the public domain. Some of the methods discussed includes how to carry out analysis of stocks, delays, and throughput analysis in production systems.

The challenges experienced in operational decision making for traditional mining were illustrated and discussion was done on justifications for use of systems and technologies such as decision support systems (DSS). The review shows that traditional mines in general do not take advantage of the data created in system to make decisions hence wrong solutions maybe implemented. DSS are useful in aiding the decision make to make better decision driven by data. The chapter thus also summarized some of the new technology developments for improved decision support and integrated mining system. Levels of decision making in an organization and how information is critical in driving decision making was also discussed.

Current developments in underground mining equipment are moving towards integration of systems, to include systems that have capability to monitor the health status of machine, geological positioning and tracking of equipment, as well as production monitoring. Use of RFID technologies as well as on-board equipment software was discussed and shown to be assisting in making real-time decision support on underground mining possible. This is also being made possible by the fast development in underground communication technologies such as leaky feeders and wireless systems.

Finally the chapter concluded by discussing important principles regarding statistical analysis relevant to a study of this nature. The study approach was chosen to be a non-experimental study which depended on study of historical data, naturalistic observations and qualitative studies which includes case study. In this case study, data collected would need to be analyzed for correlation and also interpreted for causation if need be, hence the importance of good statistical analysis.

3. RESEARCH METHODOLOGY

3.1. OVERVIEW

The intention of this research study was to investigate opportunities available in underground trackless hard-rock mining operations through improvements in production decision-making processes. The main focus was on how data can be used to drive mining production throughputs by better decision making. The research involved collecting and analyzing operational data from a number of mining operations in different parts of Africa. Various methods of data and information gathering were thus employed to accomplish the objectives, including observations by the researcher through his own work experiences.

The study was designed as non-experimental quantitative (correlational) research due to the impracticality of carrying out controllable experimental processes. A non-experimental research study is defined as one in which the researcher does not have complete control over the conditions of the study and hence cannot be subject to control and manipulation of the variables in the study (McBurney, 2001). Four methods were employed in this research, being observational research, archival, case-study, and surveys.

Production throughput analysis techniques and Lean-System Engineering (LSE) tools were used as the main tools for analysis. According to INCOSE (2011), a LSE approach applies the system engineering (SE) processes in defining and analysing a problem, while lean tools and operations research techniques are used for developing scientific solutions to the identified problems.

Buede (2009) and INCOSE (2011) show that SE approach in general takes the identified system and tries to understand and define the problem and its context before solving it. After defining the problem and its context, SE solves the problem by first decomposing the main system down into its sub-systems and further down to its components. Solution to the problem is solved at sub-system and components levels and then integrated to system level for overall solution.

In this study, the trackless mining production system was identified as the system of interest and the problem to be solved being how to improve the production output. The mining system was decomposed into its various sub-systems such as drilling and blast, load and haul, tramming, crushing and hoisting. These sub-systems were then broken further into component/equipment levels where detailed analysis was done. After defining the solutions at lower levels, the final solution to the system came from integrating the lower level solutions upwards.

Lean tools such as value stream maps were used to provide process related solutions at sub-system levels, and the other mathematical and operations research techniques were used to solve detailed equipment level problems. Figure 3.1 is a depiction of this technique.

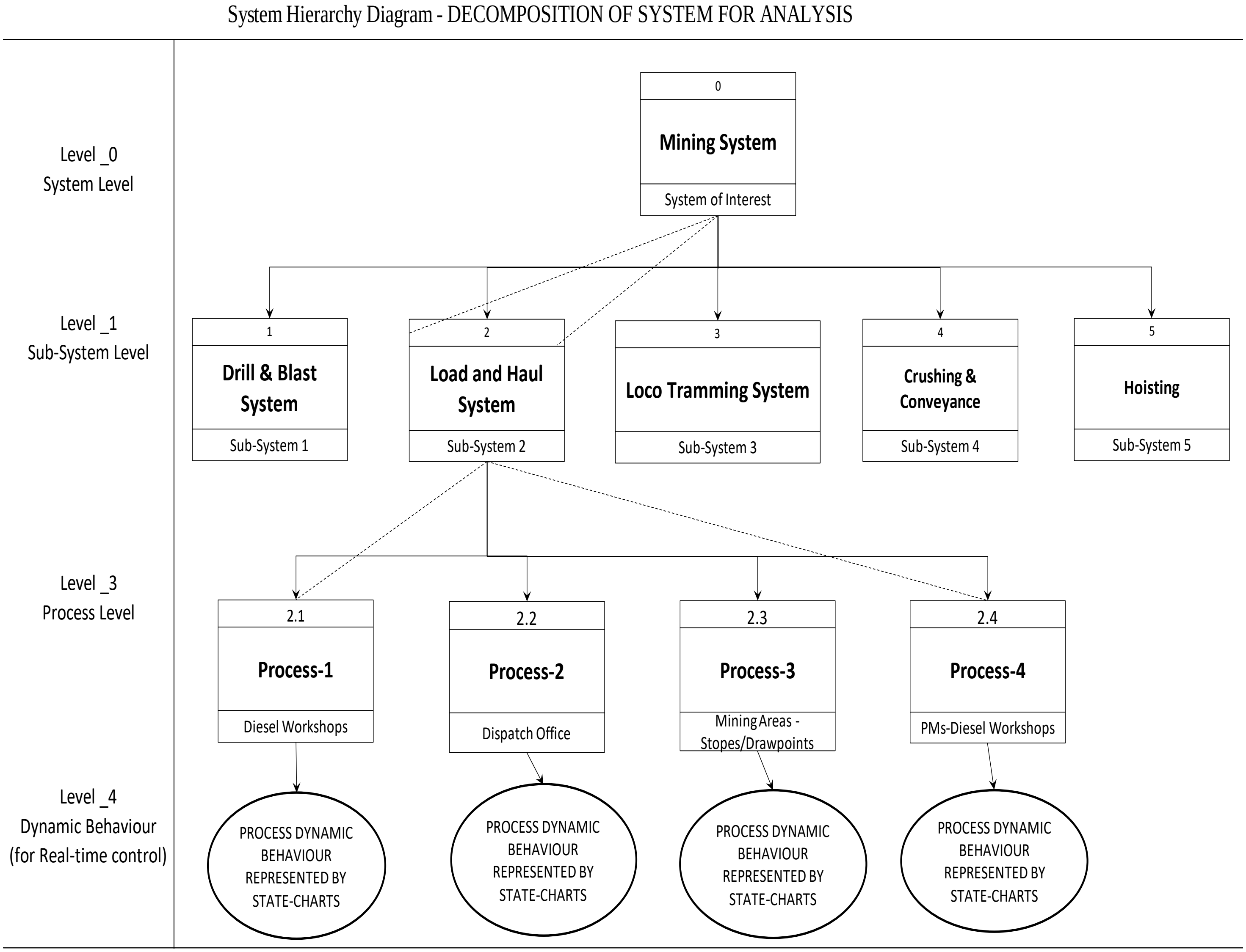


Figure 3.1 – LSE Technique for trackless mining production system analysis

3.2. REVIEWED ORGANIZATIONS

Information from 13 different mining operations was reviewed from a total of 24 that were targeted. The study involved observations from the researcher due to his employment in two of the mining organizations at MineABC and MineXYZ, an on-line survey of 18 organizations of which 7 responses were received and one selected case review of an operating mine.

The main study was a participant observer study at MineABC (not real name for confidentiality purposes). MineABC was a large nickel/copper mining organization, which had four separate operating mechanized vertical shafts. The four shafts employed manual information and data management processes which were used in decision making, being traditional mining shafts in existence for over 40 years. This allowed for good comparison and contrast to assess the impact of decision making processes. Also the mine had struggled with low productivity and poor efficiencies across its processes and presented itself as a good case for identifying opportunities for improvements.

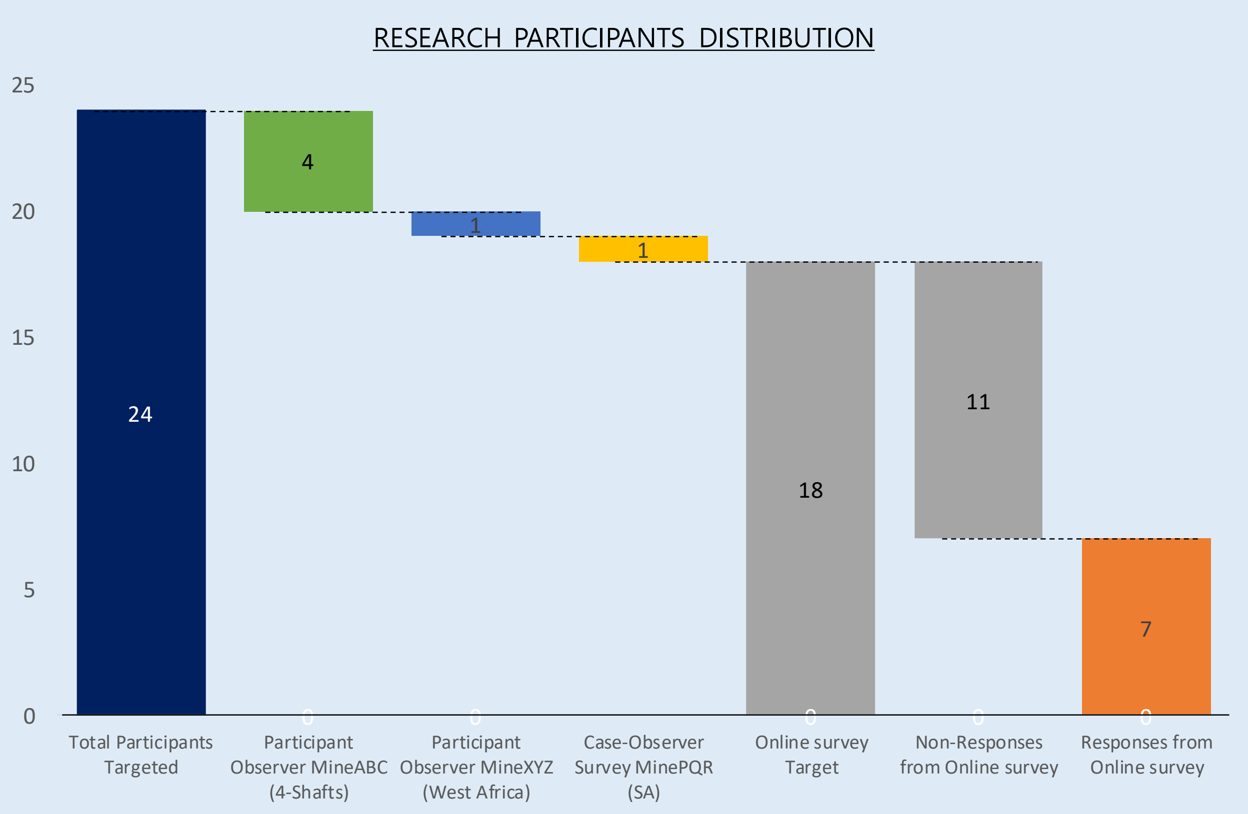


Figure 3.2 – List of reviewed mines

For the online survey, a questionnaire was sent out to 18 companies and a response from seven was received back which was a 39% response. The third study was a case observation review for a chosen mine which had an implemented and active dispatch decision support system.

3.3. RESEARCH DESIGN

This research was designed to use various methods of data collections, spanning different mines to avoid biases in the outcomes. Three research methods were used.

The first method was participant observation at the researcher's previous places of employment at MineABC and MineXYZ. The main study was at MineABC. Official access was given to the researcher by his employer for the study and also as part of the business improvement initiatives. This had the advantage of the researcher getting involved in the data generation as a participant observer as well as access to the archive records of the businesses. Equipment uptime studies, reliability studies, maintainability analysis and process observations were undertaken.

The second method employed was to use on-line survey research tools to gather data from various mines involved in trackless mechanized mining using a designed questionnaire with 36 questions to a selected audience. The participants in the survey were selected from various known mines. The online Qualtrics Research engine (www.qualitrics.com) was used to generate and transmit research questionnaires to the selected mines.

The online survey approach was to use a purposive and convenient sampling tactic. Purposive sampling is one where the sample is chosen for specific characteristics that it purposes (McBurney, 2001). In this case the purpose was to look at mines expected to be operating mechanized trackless equipment in their mining processes. Convenience was also a major consideration. Appropriate mines were chosen instead of randomly choosing mines.

The third method used was a short observation survey on a mine to benchmark in terms of an active decision support system. The survey involved the researcher visiting the mine for 2 days and carrying out observations, investigating the functionality of the system, hardware and infrastructure, and the supervisory systems.

3.4. PROCEDURE

Four research tools were used with the major aim being to collect good data for the study which could be validated and also to reduce bias. The following describes the different tools used.

3.4.1. Observational research - use of unobstructive task observations

Unobstructive task observations were used to check the different decision making behaviours in different mining settings during the researcher's employment in two of the mining organizations. According to McBurney (2001), observational research is a "study method in which the researcher observes and records ongoing behavior but does not attempt to change it".

Detailed task observation studies were carried out at the four shafts at MineABC at which mines the researcher worked as an employee, together with some minimal observation done at MineXYZ in West Africa. Times and activities were recorded as the various mine events were happening. Most of them happened as either Planned Task Observations (PTOs) and Unplanned Task Observations (UTOs) where the observed people were not made aware of the observations, to ensure that the observation is not altered to suit the requirements of the observer.

One of the main observation study was done for two weeks where an uptime study involving observation for 15 days between 5th to 19th June 2014 of mobile diesel equipment at MineABC Shaft-4 was done. In this task observation study, 413 Machine observations were made over 10-hour shifts. On average 14 machines were observed during each shift. The distribution of machine observations done was as follows - 88 drill rigs observations, 205 dump truck observations and 120 LHDs (load-haul dumpers). The focus of study was to calculate the total actual uptime or face time for each of these critical diesel machines used for production which were always not meeting the planned production outputs.

Task observations were also done in the underground maintenance and repair workshops at Shaft.3 for a period of two weeks. This involved direct observations of the tasks being done in the repair workshops during start of shifts, during equipment dispatching and during repair and maintenance activities. In total, over 200 cumulative deliberate task observations were done at MineABC.

Brainstorming sessions in April 2014 were also used as part of observer participant research tools where stakeholder input was solicited in the benefits expected from an improved decision system.

3.4.2. Archival research – historical data reviews

Archival research was one of the main methods used in this study for correlational analysis. Archival research is a type of primary research which involves seeking out and extracting evidence from original archival records and the researcher simply examines or selects the data for analysis and the researcher has no part in collecting the data (McBurney, 2001). The records studied are usually held either in institutional archive repositories, or in the custody of the organization (whether a government body, business, family, or other agency) that originally generated or accumulated them, or in that of a successor body (McBurney, 2001).

In this study collection and analysis of historical business documents, technical and management reports were used to give insights into decision making systems at the mines. A lot of historical operational data spanning 10 year period was made available to the researcher which the mines have been collecting and archiving during their operations.

Historical data on equipment performance and operational systems from MineABC for years 2014 and 2015, and production data for years 2010 to 2015 were analysed in great detail among the other various documents. This data was organized and analyzed to bring a lot of insights into the productivity, maintainability, reliability and actual capacity of the trackless equipment at MineABC. Data from MineABC’s four different operational shafts was very useful to compare and contrast the different variables as it was collected from different settings. Also the mine had been in existence for over 40 years making large archive data available for better statistical analysis.

Over 20 different documents were analyzed and below are some of the major records used in the study at MineABC: Downtime log2015 YTD-Dec, Equipment availability records, Mining efficiencies and production, Hoist and Compressors performance record, Diesel equipment performance records 2015, Operational and Engineering downtimes, LHDs loading records, Operational costs records, Monthly management reports, Costs Reports – ShaftA3 New mine plan

07032016, ShaftA3 – Daily Availability Records 2013, 2014 & 2015, Scooping and loading records 2014 – 2015, Production Figures 2010 – 2015, Stoping 2015 – ShaftA3, Working area – tipping points, Process Audit Reports, and Mine design and optimization studies

3.4.3. Case Observation

Case studies examine individual cases of some phenomenon using various methods and they normally result from problems that present themselves to researchers as opportunities that must be grasped quickly or lost (McBurney, 2001). A purposefully selected case review was used as a comparative study to benchmark the findings from the other mines methods. This study was done at MinePQR, which operated a fully functional decision support system using a commercial mining Dispatch system.

The researcher was able to go and physically observe the system in operation and interacted with key operational and maintenance personnel using and maintaining the system for 2 days. The architecture of the system was observed. Records from the system were extracted and analyzed.

3.4.4. Online Surveys

Surveys are another method of collecting and gathering scientific information (McBurney, 2001) and in this study non-random sampling using online tools was used in gathering information from various mines.

A total of 18 survey questionnaires were send out of which a response from the seven was received. This makes a 39% response rate. The issue of response rate is always an issue with survey research and according to McBurney (2001), mail surveys have a return rate of between 10% to 50%. The questionnaire was sent out to either the engineers or production supervisors of the mines as they were deemed to be direct users of mobile diesel equipment in the mines.

The questionnaire had 36 questions and was divided into two broad sections. First section focused on mining systems and fleet productivity with 22 questions, and second section focused on decision support systems and associated support infrastructures and technology with 14 questions.

3.5. ANALYSIS AND INTERPRETATION OF DATA

3.5.1. Data Source

The data collected was used in carrying out detailed analysis of the production systems with aim of identifying factors which affected mining system throughput capacity at the mines under study. Aldien's method as adopted by Blumerfield (Alden, et al., 2006; Blumenfeld & Li, 2005) was applied in calculating the important and key decision factors in throughput analysis for MineABC production system. This was due to the availability of large operational data from the mine.

As discussed in section 2.2, and assuming and taking the mining production system as a parallel, serial production system (Li, et al., (2009), MineABC's parallel processes were modelled into an equivalent serial production system with the different work stations components connected to each other in series. Key factors which impact throughput such as failure rate, repair rates, availability indexes and capacities were then calculated from the operational data collected.

3.5.2. Use of Stocks, Materials in Transit and System Delay/Lead times

A production system can be defined by the inflows to the system, the stocks of material in transit which is the work in process (WIP), and the output from the system. The availability of material in transit introduces delays in the system which need to be managed. Figure 2.3 given in Chapter 2 defines a generic materials stock flow diagram for a production system. This was re-modelled for a trackless mine production system as illustrated in Figure 3.3

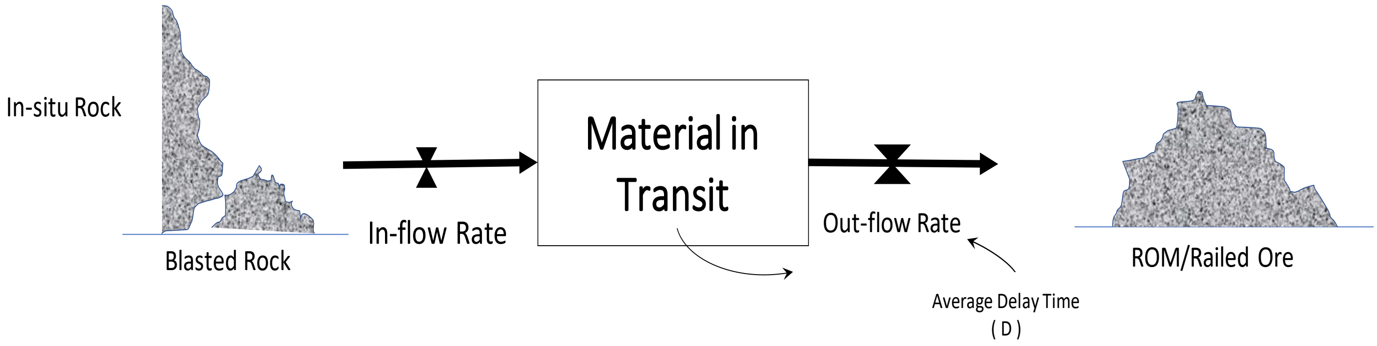


Figure 3.3 – Model of a mine production process with material in transit

Formulae from Sterman (2000), were used to calculate the outflow rate for the mine's production system versus the residence times and show it as a function of the Stock/Material in Transit as was given by equation (2-1) to (2.4) in Chapter 2, namely:

$$\text{Stock, S(t)} \quad = \quad \int_{to}^{t}[Inflow(s) - Outflow\ (s)]ds\ + Stock(to) \qquad (2.1)$$

From initial time t_o to time t. The differential equation for stock represents the net rate of change of stock and is equivalent to inflows less the outflows.

$$\text{d [S(t)]/dt} \quad = \quad \text{Inflow(t) – Outflow (t)} \qquad (2.2)$$

If D represents the average delay or residence time of the stock in the system, the outflow is given by:

$$\text{Outflow} \quad = \quad \text{Material in Transit / Average Delay Time} \quad = \quad \text{S(t)/D} \qquad (2.3)$$

or,
$$\text{Average Delay Time (D)} \quad = \quad \text{Material in Transit/Outflow} \qquad (2.4)$$

Material in transit consists of the ore generated plus the stock already in the system less the ore outflowing. From equation (2.4), to maximize the ore outflow, the ore in transit must be maximized and the average delay time (ore residence time) in the system must be minimized.

Residence time looked at the time for broken rock to flow through the system after breaking it, until it was on surface as Run-of-Mine (ROM) ore. These parameters were useful for indicating which areas are constraints to the total output.

The equations (2.2), (2.3) and (2.4) were used in calculating the ore residence times in the different cascading work stations as well as calculating the overall system delays.

3.5.3. Model of a trackless mine production system

The Alden, et al., (2006) and Blumenfeld & Li (2005), models for serial production systems were used in assessing work stations reliability and maintainability performance. According to Alden, et al., (2006) and Blumenfeld & Li (2005), if a mine production system could be treated as a serial stochastic production system, then each process area can be defined as a work station or work centre made up of one or more similar machines represented by the model below in Figure 3.4.

In Figure 3.4, circles were used to represent the buffers and squares to represent the different work stations. Work stations in this case of a trackless mining system were the drilling and blasting work stations, load and haul stations, tramming stations, crushing stations and hoisting stations.

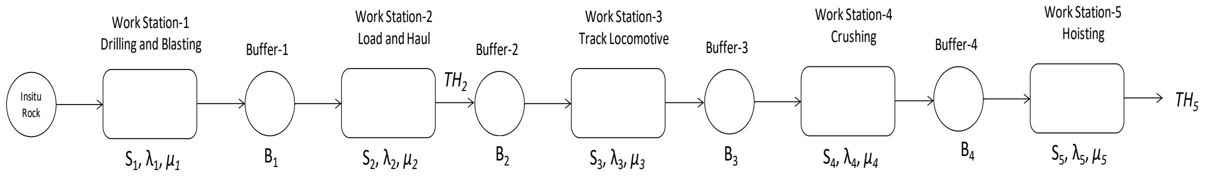


Figure 3.4 – Model of a trackless mining production system with buffers

Stochastic production lines are subject to disturbances arising from variations in processing times and failures of the work stations involved (Alden, et al., 2006; Blumenfeld & Li, 2005). This can cause the machines to be idle and can lower the throughput of the line.

The quantity of output a work station can produce per unit time is the *speed* (or *service rate*) of that station. An example is the number of tons produced every cycle at the drilling and blast station. The production of one output quantity or lot size (e.g. a truck load of ore) is a *cycle*. The time to produce one lot size, when there is no station failure is then the *cycle time* (or service/processing time).

If the station is subject to failures, the frequency of failures is determined by the *failure rate (*λ) and the rate of repairs per unit time is determined by the *repair rate (*μ*)*. The ratio of the operating time to total time is the station's availability (or standalone availability) represented by the availability index (*Avail*). The number of lot sizes the station can produce per unit time, considering the failures, is the station's throughput (or standalone throughput) (*TH*).

The following definitions and symbols were used to describe the station parameters:

- LS – lot size, which is the target quantity produced per cycle of production. Can be truck load, loader bucket, advance/blast, etc.
- PS – Ideal station throughput, which is number of LS moved per unit time without failures (rated capacity)

- CT – cycle time of the station to move a LS, ton of ore/trucks of ore
- TH – throughput rate - LS moved per unit time of production (e.g., truck loads/h), considering the station failures
- OT – Operating hours per day - actual time station is being used for production purposes – this is time remaining after considering of production delays and standby
- CO – changeover time
- UP – % uptime of system
- UT – % utilization of the system
- MTBF – mean operating time between failures
- MTTR – mean time to repair after failure of system elements (mean downtime)
- λ – failure rate (number of failures per unit time, equivalent to 1/MTBF)
- μ – repair rate (number of repairs per unit time, equivalent to 1/MTTR)
- PPT – Planned production time - time per day/shift planned for production activities - time remaining after considering the practical shift cycles and dead time such as set blasting times as per mining regulations and fixed travelling times
- DT – Downtime hours - total time the plant is mechanically unavailable for use due to scheduled and unscheduled stoppages and not available for production purposes.
- AT – Available hours – time production plant and facilities are mechanically for production uses - time remaining after Scheduled and Unscheduled stoppages.

Then, for a single station,

$$\text{Cycle time, CT} = \frac{1}{PS} \tag{3.5}$$

$$\text{MTBF} = \frac{1}{\lambda} \tag{3.6}$$

$$\text{MTTR} = \frac{1}{\mu} \tag{3.7}$$

$$\text{Stand-alone Availability, } Avail = \frac{MTBF}{MTBF+MTTR} = \frac{\mu}{\mu+\lambda} \tag{3.8}$$

$$\text{Throughput rate, } TH = (\text{Availability x PS}) \tag{3.9}$$

However, for a two-station model, the equation becomes more complicated. Using Alden, et al., (2006)'s two-station model representing two work stations arranged in series and connected by a buffer shown in Figure 3.5:

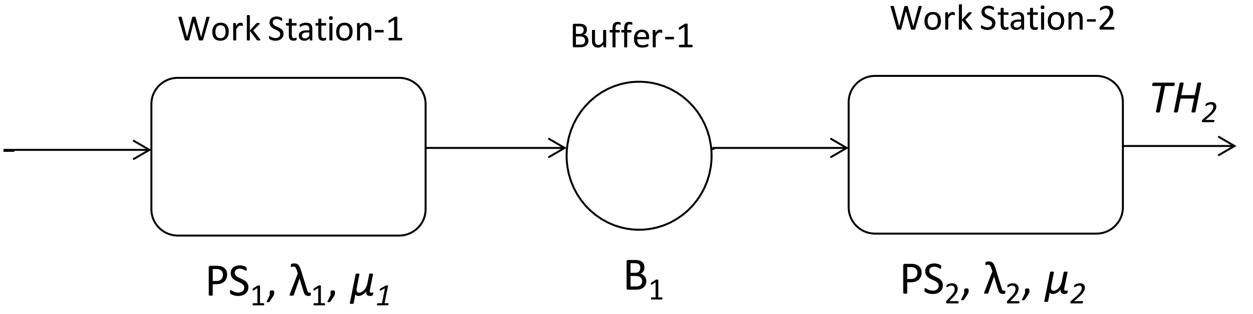


Figure 3.5 – a two station production system with buffer

The parameters for throughput rate calculations are defined as follows:

(i) PS_i, the speed of station i (i=1,2) (jobs per hour),

(ii) λ_i, the failure rate of station i (i=1,2) (failures per hour),

(iii) μ_i, the repair rate of station i (i=1,2) (repairs per hour),

(iv) B, the buffer size ($0 \leq B < \infty$) (number of jobs).

(v) The speed PS_i is the number of jobs station i processes per hour when not blocked, starved, or failed.

(vi) The failure rate λ_i is the number of failures per hour of operating time, that is, $1/\lambda i$ is the mean operating time between failures ($MTBF_i$) (i=1,2).

(vii) The repair rate μ_i is the number of repairs per hour, that is, $1/\mu i$ is the mean time to repair ($MTTR_i$) or mean downtime (i=1,2).

(viii) The buffer size B is the number of jobs the buffer can hold.

(ix) For given reliability parameters λ_i and μ_i, the fraction of time that station i is available for processing jobs if never blocked or starved is

$$\frac{\mu_i}{\lambda_i + \mu_i} \quad \text{or} \quad \frac{\text{MTBF}_i}{\text{MTBF}_i + \text{MTTR}_i}. \tag{3.10}$$

This fraction is known as the station's stand-alone availability or efficiency (Alden, et al., 2006).

The effective speed $\hat{PS}_i$ of station i, accounting for its stand-alone availability, is therefore

$$P\hat{S}_i = PS_i \left(\frac{\mu_i}{\lambda_i + \mu_i}\right) \quad (i = 1, 2) \tag{3.11}$$

The speed PS_i in equation (3.11) is often referred to as the station's stand-alone throughput.

In the special case where the stations are similar, i.e.

$$PS_1 = PS_2 = PS, \qquad \lambda_1 = \lambda_2 = \lambda \quad \text{and} \quad \mu_1 = \mu_2 = \mu \tag{3.12}$$

Then the station throughput at station 2, TH_2 in loads moved per hour is given by,

$$TH_2 \text{ (loads/h)} = \mathrm{PS} \left(\frac{1}{1+2(\lambda/\mu)}\right) \left(1 + \frac{(\lambda/\mu)(\mathrm{B}\mu/\mathrm{PS})}{2+(1+\lambda/\mu)(\mathrm{B}\mu/\mathrm{PS})}\right) \tag{3.13}$$

Equation (3.13) was used to model and calculate the various impact of reliability, maintainability and capacity factors that influence production throughput in a typical trackless system.

An important derived equation from (3.13) is the production rate (Q) in tons per hour. Production rate is the throughput rate in loads moved per hour multiplied by the bucket factor (BF) in tons/load of each load. Example is for a 10-ton rated loader, the actual tonnage moved by a bucket might be only 6.5 tons due to the density of the material as well as the fragmentation, giving a bucket factor of 65%. Therefore, production rate (Q) in tons/h is given by equation (3.14) :

Production rate (tons/h) = Throughput rate (loads/h) x Bucket Factor (tons/load)

$$Q \text{ (tons/h)} = \text{TH (loads/h)} \times \text{BF (tons/load)} \tag{3.14}$$

3.5.4. Key assumptions and interpretation of data

The study, being effectively a correlational study, employed statistical analysis techniques to analyse and interpret historical data. The key methods employed included calculating the central tendency of data through the mean, calculating the data variability through variance and standard deviations, calculating the correlation and regression between the various variable in the production process such as impact of availability index $\left(\frac{\mu}{\mu+\lambda}\right)$ on throughputs and the various relationship between failure rates, repair rates and capacities.

The key assumptions used in the interpretation of the data were:

- That the data and variables to be used in the study would exhibit linear and non-linear properties, hence both linear and non-linear correlation and regression techniques would be applicable and used to check for correlation and interpretation of causation if identified. This is because the data used in the study is actual data generated during the normal operation of the organization and hence no deliberate manipulation of the data is expected.

- A linear relationship will be of the form: $Y = \beta_0 + \beta_1 X + \varepsilon$, (3.15)

  Where: Y = Response (dependent) variables

  X = Explanatory (independent or predictor) variables
  β_1 = Regression Parameters, constant over all cases
  ε = Residual (or Random Disturbance or Error) variable which varies over all cases. The random errors have zero mean and are assumed to have common variance σ^2 and to be pairwise independent.
  β_0 = Represents the intercept of the best fitting line

- A non-linear relationship will also be of the form, $Y = f(\theta, X) + \varepsilon$, (3.16)

  Where the expected response are non-linear functions of the parameters, and θ is used to represent the parameters to distinguish from linear parameters , β_1

- A Correlation Coefficient was used to describe correlation between data. In this study the correlation coefficient will be taken to be significant when above ±0.5. The formula for the correlation coefficient is given for X and Y variables by, r_{xy}:

$$r_{xy} = \frac{\Sigma XY - \frac{(\Sigma X)(\Sigma Y)}{n}}{\sqrt{(SS_x)(SS_y)}} \qquad (3.17)$$

  Where, SS_x = Sum of squares for X variables,

  SS_y = Sum of squares for Y variables

$\sum X$ = Sum of explanatory (independent or predictor) variables

$\sum Y$ = Sum of response (dependent) variables

$\sum XY$ = Sum of product of X and Y

n = number of sample pairs analysed

Figure 3. Is the guideline to be used to describe the strength of the relationship between variables based on the correlation coefficient.

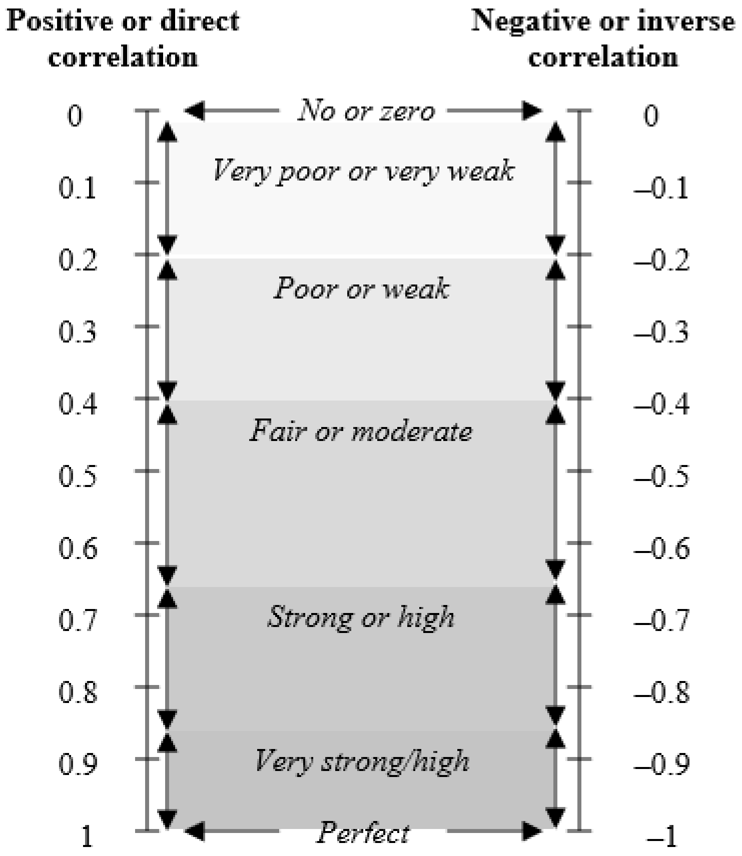


Figure 3.6 – Decision guideline for correlation coefficient (Correlation Analysis, 2018)

- Parameters estimates for both linear and non-linear regression relationships were obtained using “Methods of Least Squares” to obtain best fit and testing whether residuals are randomly distributed, i.e. they approximates to normal distribution.

- Coefficient of Determinations or Regression coefficient, R^2 *was an important parameter which was* used to test for how good the relationships between the X and Y variables was and was calculated as:

$$R^2 = \frac{\mathrm{SSR}}{\mathrm{SST}} \tag{3.18}$$

Whereas, SSR is Regression Sum of Squares, SSR = $\sum_{i=1}^{N}[(\hat{\mathrm{Y}}\mathrm{i})error - (\bar{\mathrm{Y}})error]2$

And, SST is Total Sum of Squares , SST = $\sum_{i=1}^{N}[(\hat{\mathrm{Y}}\mathrm{i})observed - (\bar{\mathrm{Y}})observed]2$

The higher the value of R^2 (closer to 1), the more important the relationship.

Where $\hat{Y}_i$ – represents the reading at i = 1, 2, 3 ……N

$\bar{Y}$ – represents the mean reading of the population.

- 95% significance level ($\alpha = 0.05$) was as a measure of significance, on the standard Student t-Test.

- Analysis of residual errors were used to identify data errors which are more **influential** as well as identifying/detecting **outliers** in the data

- Chapter 4 considers these variations and analyzes the potential benefits of improved analysis of system throughputs.

4. ANALYSIS - KEY FACTORS IMPACTING MINING THROUGHPUT

4.1. CHAPTER OVERVIEW

The total tonnage which can be produced in a mine per time depends on the production rate of the mine multiplied by the effective hours the mine is operational. The production rate in tons per hour is a function of the throughput in loads per hour and the bucket factor as given by equation (3.14)

A mine is made up of various work stations which make up the production system. Therefore, for a given throughput rate represented by TH (loads/h), total effective operating hours, OT (in hours), and a bucket fill factor, BF (tons/load), then the total production in a given period for a work station can be given by, Q_T(tons) : Q_T *(tons)*= Q (tons/h) x OT (h), therefore

Total Tonnage = Throughput rate x Total Effective Utilized Hours per period x Fill factor

$$Q_T\ (tons) = TH \text{ (Loads/h) x OT (h) x BF (Tons/load)} \tag{4.1}$$

This chapter analyses critical technical factors which impact throughput rate (TH). Chapter 5 analyses system factors which impact the total operational hours (OT).

This chapter is structured in two main sections. The first part covers decisions that impact capacity at system and process level, while the second part covers work station/equipment level decisions.

Actual operating data from MineABC for year 2015 was used in the study. Production throughput calculations for a serial production system together, theory of constraints (TOC) and lean system engineering tools like value stream mapping were employed in quantifying the possible benefits.

4.2. BACKGROUND AND CONTEXT OF PROBLEM – CASE STUDY MINE

4.2.1. Production scenario of MineABC

A typical mining process is cyclic in nature involving ore drilling and blasting, face preparation, loading and hauling, roof support and then tramming and hoisting of the blasted ore to surface. MineABC was a trackless production system which employed mobile rubber tyred diesel/electro-hydraulic powered equipment for mining and transporting the ore.

The equipment included drill rigs and roof support bolters, load and haul dumpers (LHDs) and articulated dump trucks (ADTs) for mining. Supporting fixed plant included primary crushers, belt conveyances, and vertical and inclined rock shafts for ore handling and conveyance processes. Track equipment (locomotives) was also used in some cases for secondary ore transportation. Figure 4.1 illustrates the concept of the mining system at MineABC.

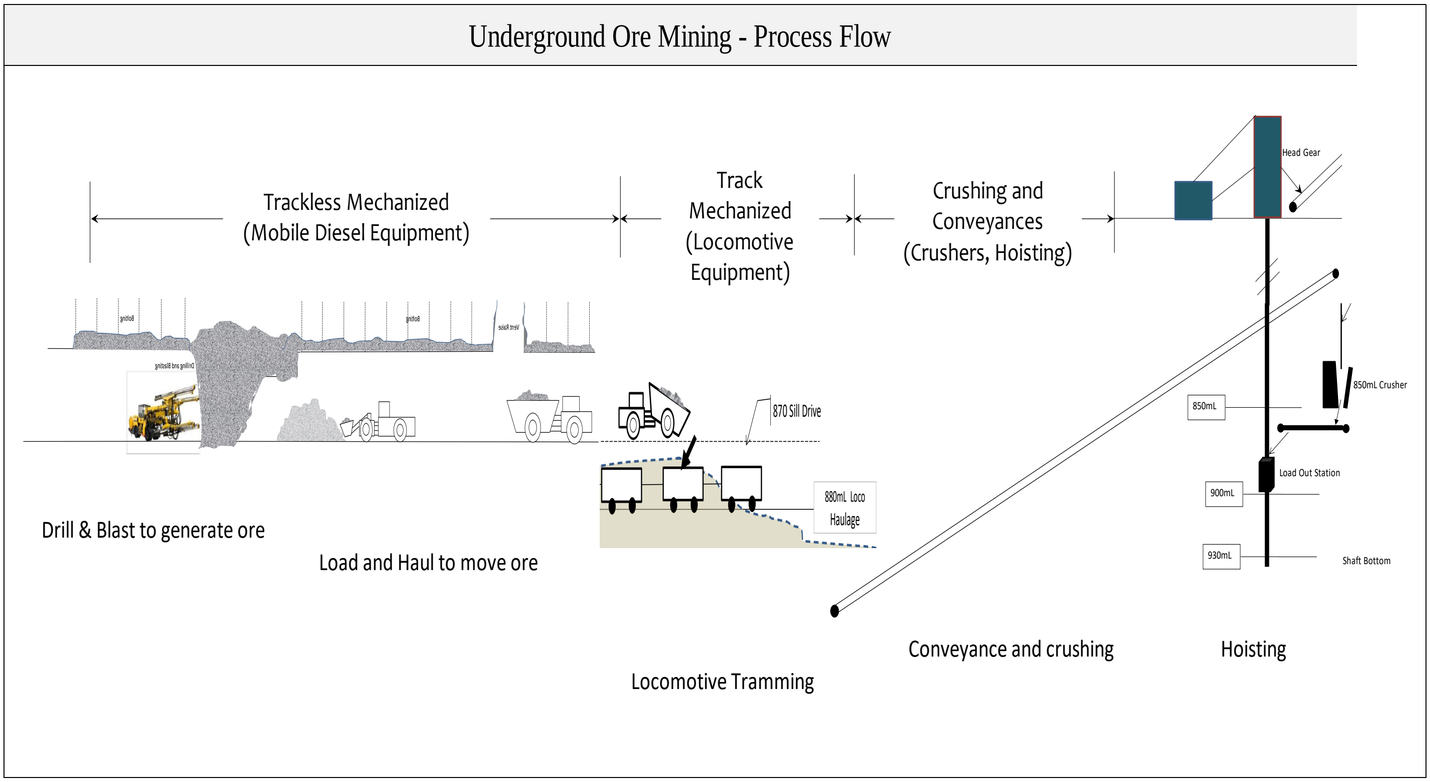


Figure 4.1 – Concept of an Underground trackless mining system with vertical (ShaftA3)

In a trackless process, the production face is continuously advancing and mining conditions changing as production goes on. The whole mining process can then be modeled as a batch process with work stations at each stage of the process which occur independently of each other.

This can be illustrated by different work stations which are linked together by buffer storages from each stage to the other as in Figure 4.2. Rectangles represent work stations such as drilling and blast stations with various machines and a circle represents a storage system or buffer.

MineABC was a nickel mine which had four production shafts identified as Shaft A1, A2, A3 and A4 which were budgeted to produce about 8,060 tons of sulphide ore per day. For ten consecutive years, the production at MineABC was declining shown in Figure 4.3.

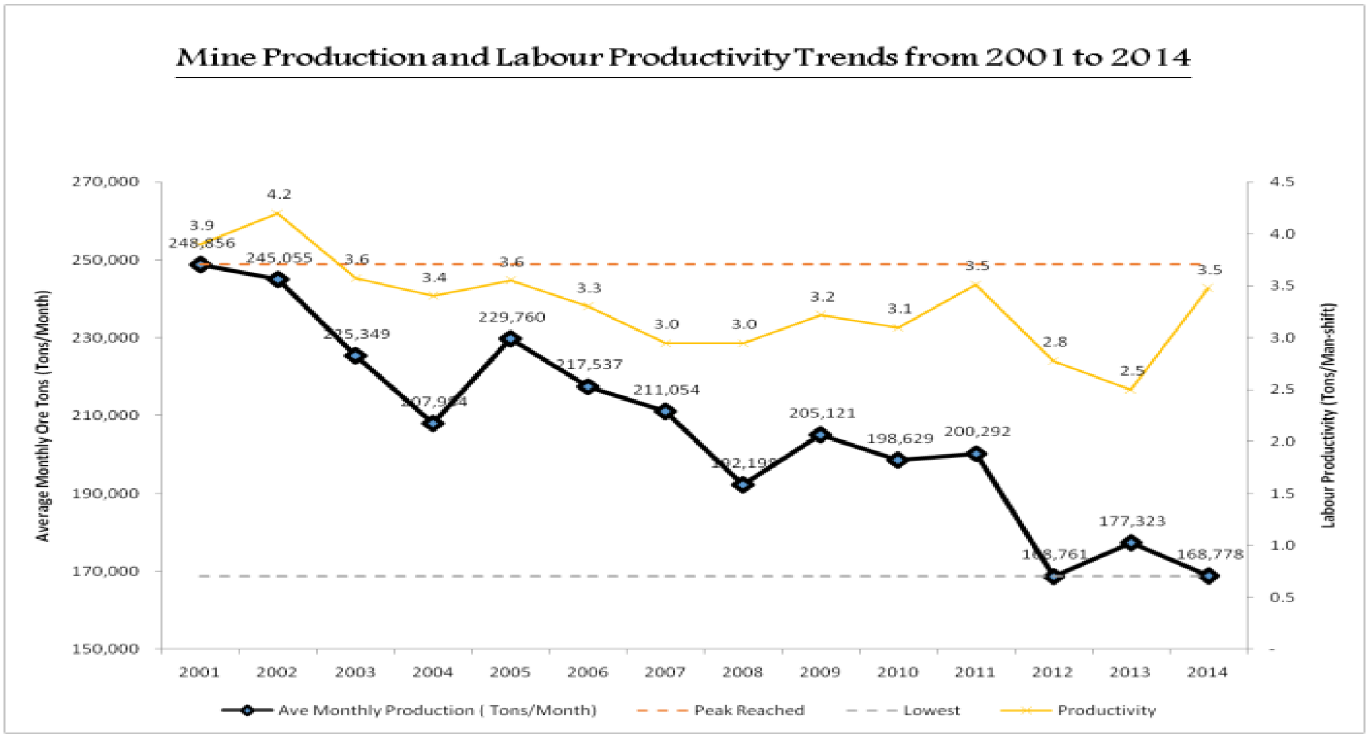


Figure 4.3 – MineABC Productivity Trends 2001 to 2014

Possible causes of the decline in production includes the difficulty in accessing ore as the mines got deeper, delays in mine development to allow access to ore, ageing and low reliability of equipment, and skills shortage. This study however, focused only on the impact of equipment performance and reliability and how it possibly affected production throughputs during the period.

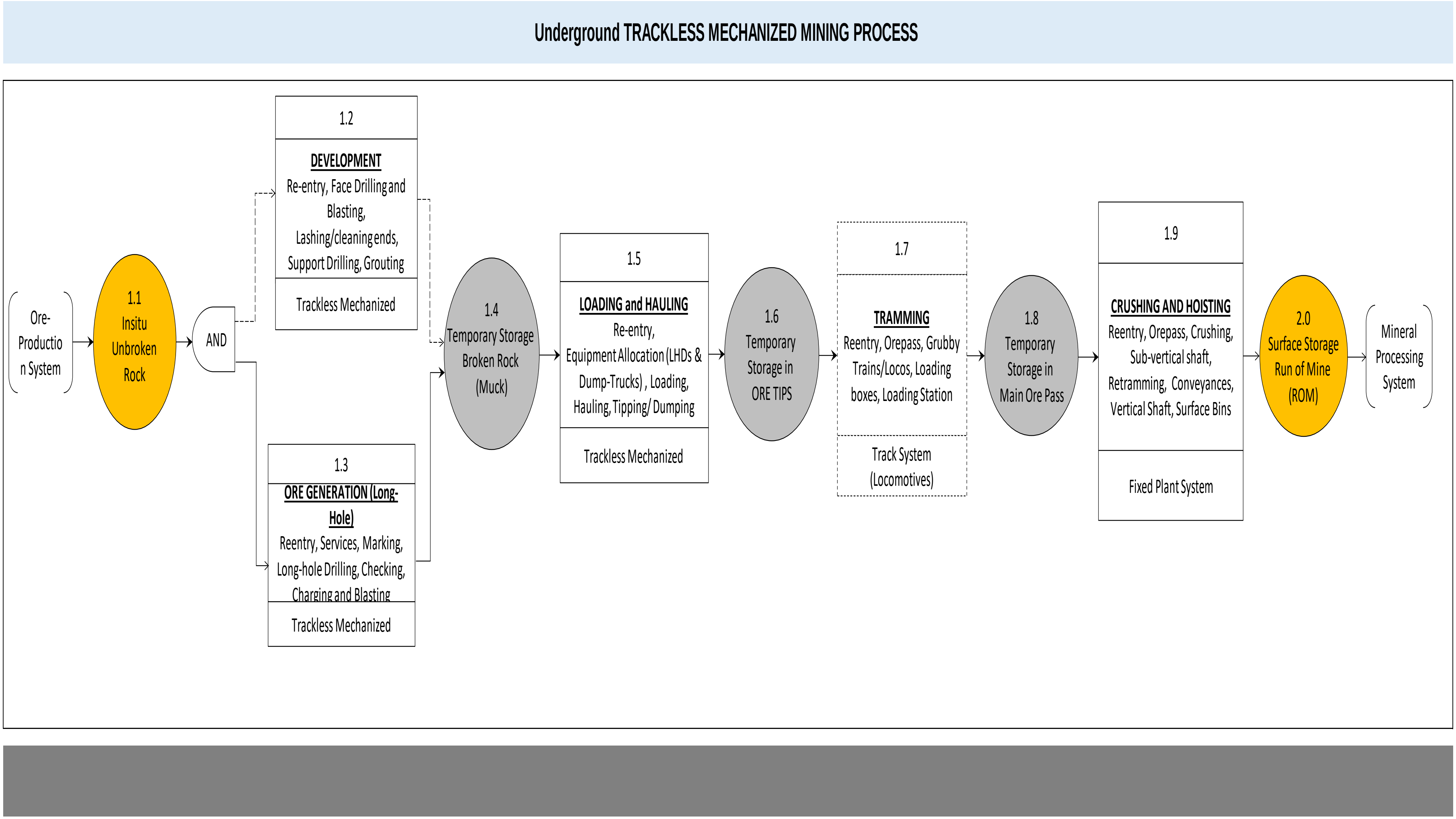


Figure 4.2 – Production process flow -Underground trackless mining system with vertical shaft

This problem was also compounded by a consistent decline in metal prices during the same periods. Historical Figures extracted from the Kitco (2018) website shows also a consistent drop of the nickel prices for the analyzed duration with the price stabilizing at below the US$10,000/ton mark during that period versus previous highs of up to US$26,000/ton (Appendix A.1).

4.2.2. Identifying system constraints in the production processes

The production scenario at MineABC required drastic interventions to turn around the business to profitability. This study was motivated by the need to get a better picture and understanding of the challenges MineABC was facing as the researcher was an employee of the mine during that period.

To quantify challenges the mine was facing, a full analysis of the production system of MineABC was done for the year 2015. The study looked at the dynamics of the production system at the mine and opportunities that could possibly be exploited to turn around things. Figure 4.4 show the actual versus target production of the mine in year 2015, and illustrates the tonnage lost opportunities.

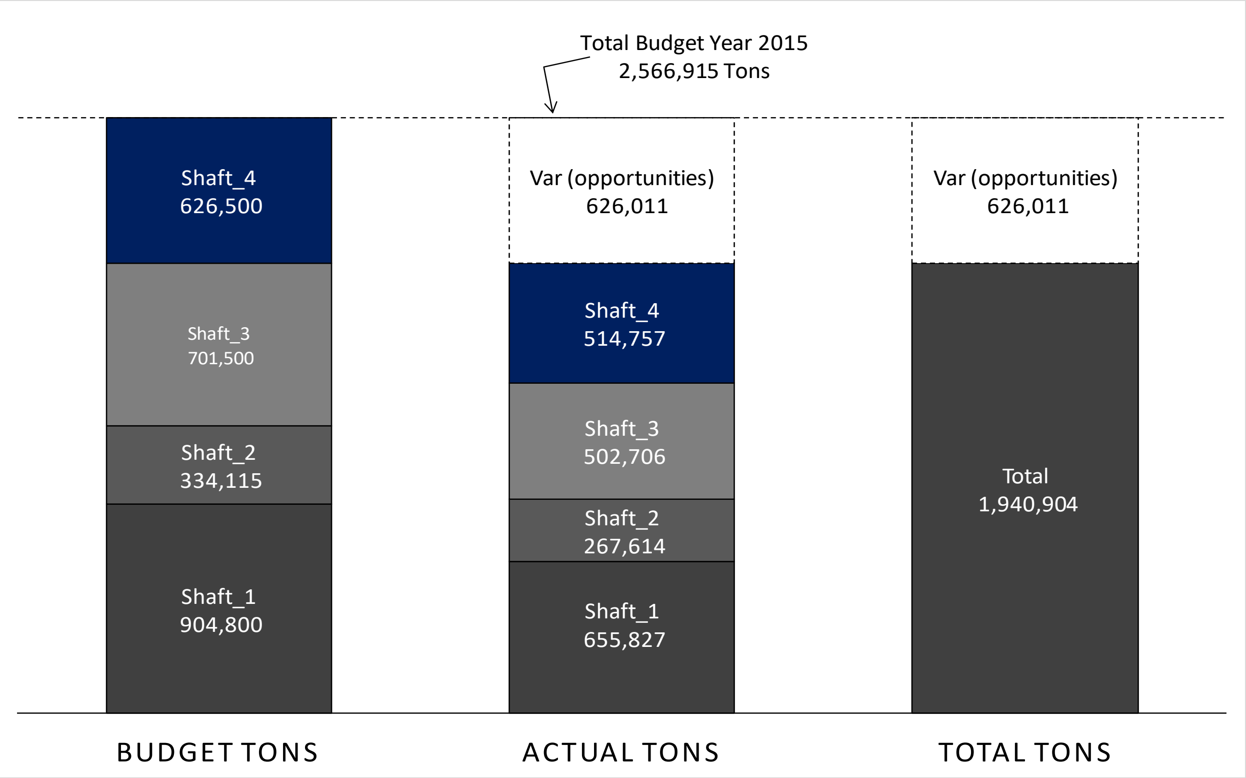


Figure 4.4 – Year 2015 budget tons vs actual for MineABC

Furthermore, a situational observation at the shafts also indicated various operational challenges on a day-to-day basis. There was an observable value loss due to improper, poor, wrong and delayed decision making observed in: equipment availability and reliability issues, poor breakdown responses, late equipment dispatch, poor or late employee dispatch, hoisting delays, locomotive and haulage breakdowns.

Management reporting was mostly reduced to history report making as there was poor visibility of the mining processes during the shifts and thus very poor short-time interval controls. Sources of information were mostly from various spreadsheets on shared folders, there was no “one source of truth” for the mines to align decisions to the business strategy at all levels all the time.
Integrity of information was a big challenge; wrong information resulted in wrong decisions and actions being taken, such as breakdown and equipment downtime information and the associated reports. Various spreadsheets were used in different sections giving different meaning of performance per section. There was no way of understanding or feeling the pulse of the business on a minute by minute or short-term basis to ensure sustainability of strategic issues.

If the factors which had an impact on the fall in the production rate were made visible early, better interventions could probably have been made in time to reverse the trends. This study considers decisions that could have been made to improve the performance of the business during this period.

4.3. SYSTEM VALUE DRIVERS

4.3.1. Value driver tree for MineABC

For an improvement to be justified, it is critical to understand what value is generated in the mining system and how decision-making influences value creation. The value driver trees (VDT) is a tool which can be used to detect and improve visibility of system elements and functions that drive value across the whole production chain for better decisions making and continuous monitoring of the elements.

If profitability of a business is one way of defining value for the stakeholders, then value can be defined as:

$$\text{Price x Volume} - \text{Costs} = \text{profit} \qquad (4.2)$$

Based on equation (4.2), Figure 4.5 is a VDT for MineABC in the year 2015 showing the profit generated for each ore mined. The mine was selling its nickel and copper matte to refineries outside the country. At the time, the contractual weighted average selling price of Nickel and Copper metal the mine was selling to the refineries was pegged at US$6,810/ton metal.

The VDT Figure 4.5 show that the business was making a loss of US$27.38 per each ton hoisted against an initially predicted profit of US$88.67 per ton. The main drive of the loss was the budgeted price of metal which was at that time US$17,637 ($8/lb.) and as well as the mine not meeting its production volumes.

MineA - VALUE DRIVER TREE ANALYSIS FOR EVERY HOISTED TON OF ORE - Year 2015

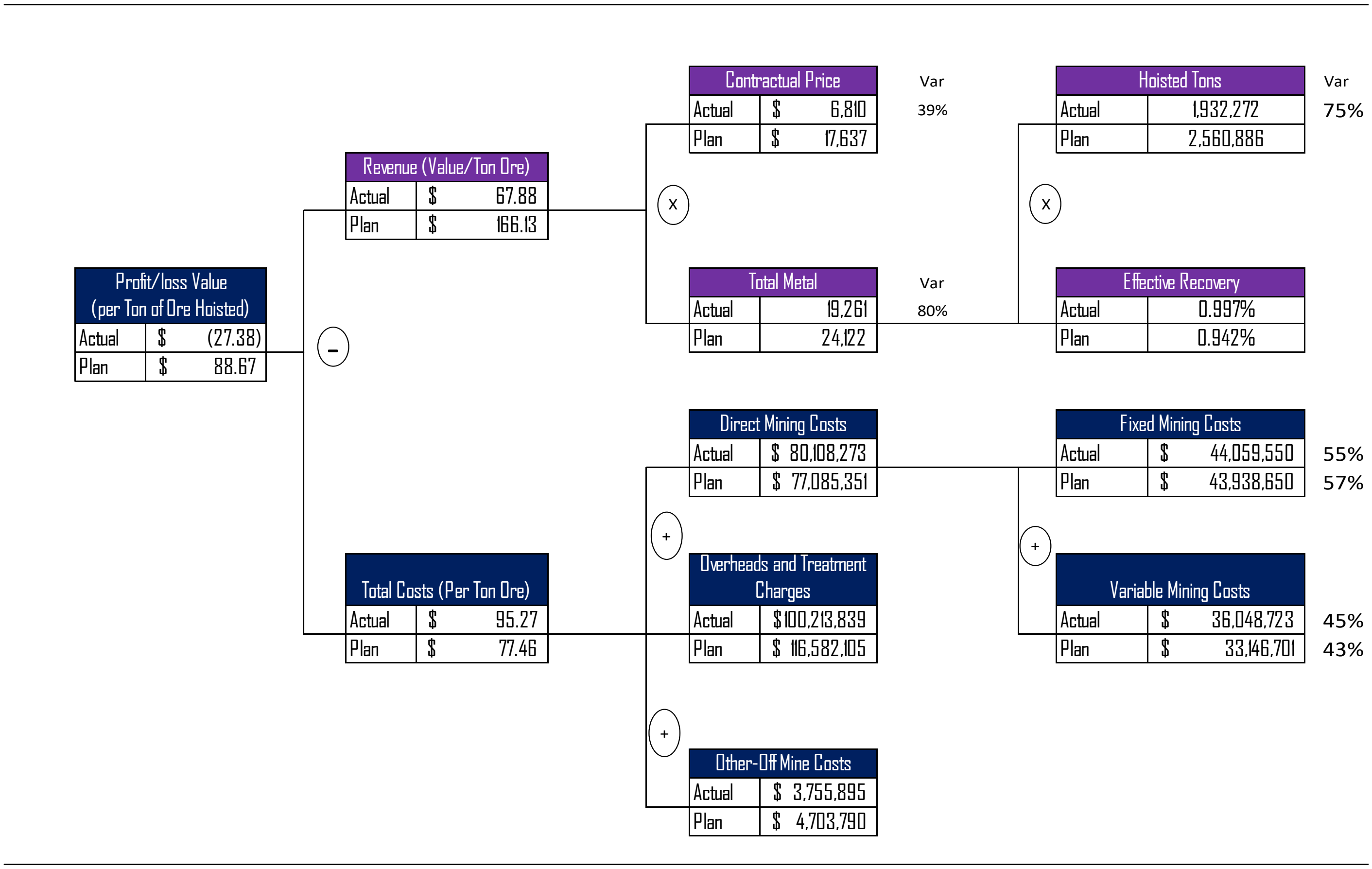


Figure 4.5 – MineABC value tree for year 2015 (Source-MineABC Monthly Reports)

Equally the same, If the mine operating costs and production were assumed the same, the VDT can be modelled to show the profit at the 2015 prices but the mine being able to reach the budgeted tons. The VDT is shown in Appendix B2. The VDT showed that the mine would still had made a loss of US$13.32/ton if it operated at the budget tonnage of 2,560,886 tons/year (213,407 tons/month). Therefore to calculate the actual breakeven tonnage the available past production statistics had to be considered to check the trends and dynamics over the previous periods.

4.3.2. MineABC profitability decision equation based on past performance

The following analysis looks at the mathematical relationship between MineABC costs and profitability and how they were related to the volumes of ore mined based on the history. The aim was to identify the impact of mining volumes on driving business profitability. Using information and data from the management reports, an analysis of quarterly periods from 2013, 2014 and 2015 was done. The analysis data is shown in Appendix B2

Figure 4.6 below show the pattern of mine tonnage profile superimposed on the profitability of the business for the same time. Figure 4.4 indicates that at the same time as the metal prices were dropping, there was also a consistent drop in tonnage for the mine during the period which was a double concern for the mine.

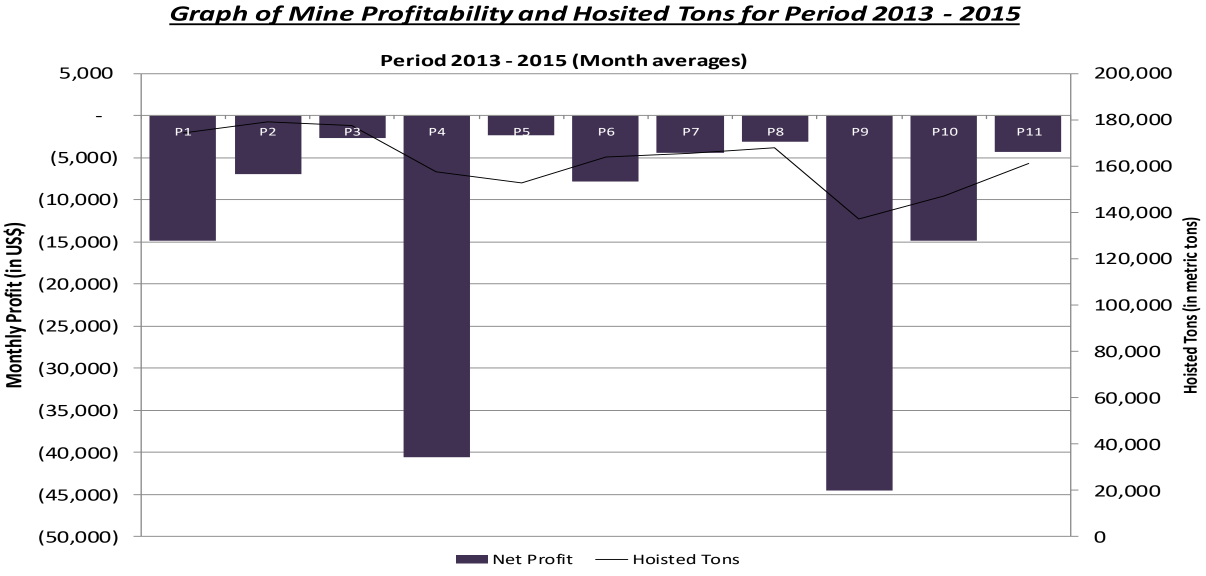


Figure 4.6 – MineABC operating profit and hoisted tons 2013-2015 (Source-Monthly Reports)

Since the mineral price could not be manipulated internally but were now stabilizing at a new low value of as low US$3.5/lb. of metal year instead of budget US$8.0/lb., the two most important value adding variable which the mine could possibly have had control over were the variable costs and the total tons of ore hoisted.

If we define the following parameters and using equation 4.2:

P = Operating Profit, in US$
R = Total Revenue, in US$
C_T = Total Costs, in US$
Л = Effective process recovery, an efficiency factor
Q = Quantity of ore hoisted or moved, in tons
M = Total Metal Produced, in metric tons
Q = Total Hoisted Tons of ore, in metric tons
SP = Metal selling price, $/ton

From the VDT Figure 4.5, C_T is made of mining costs, treatment/processing costs of the metal and other off-mine costs. The total mining costs are made up of variable mining costs plus fixed costs. Variable mining costs are those that depend on the quantity of ore mined and hoisted. Treatment costs depend on the amount of metal processed.

Therefore, Total Costs = [(Mining Costs) + (Treatment Costs) + (Other off-mine costs)] (4.3)

Mining Costs = Variable costs + Fixed Costs (4.4)

Then Profit from sale of metals, P can be calculated from the Value Tree Diagram to give.

Profit = Total Revenue – Total Costs

Profit = Total Revenue – [(Treatment Costs) + (Mining Costs) + (Other off-mine costs)] (4.5)

Therefore, profit can be assumed to be of the form.

Profit = Revenue – [(Treatment Costs) + (Variable + Fixed) + (Other off-mine costs)] (4.6)

If a focus is made to manipulate the hoisted tons, the equation can be written in a mathematical form below based on the following assumptions:

→ Treatment Costs $\propto$ Metal sold (M)

→ Variable Costs $\propto$ Quantity of Ore Hoisted (Q)

→ Other Off-mine costs are fixed, such as port charges, etc.

→ Total Metal sold is proportional to quantity of ore in the form - $M \propto Q^n$

→ Treated metal is proportional to quantity of ore in the form - $M \propto Q^{n-1}$

Where, n, being an index and K_1, K_2, K_3 and K_4 are constants to be determined.

Therefore, $P = R - C_T$ (4.7)

$P = SP.\ M - [(K_1.\ M + K_2) + K_3Q + K_4]$ (4.8)

$P = SP.\ (\text{Л}\ Q^n) - K_1.\ (Q^{n-1}) - K_2 - K_3.\ (\text{Л}\ Q) - K_4$ (4.9)

Equation (4.9) is a variation of Profit versus the hoisted tons (Q). To determine equation (4.9), a scatter plot was used. Data for total tons hoisted was plotted against the profit for the years between 2013 to 2015. The data was then extrapolated and through iterations, a line of best fit was created as illustrated in Figure 4.7. This Figure gave a cubic function, represented by equation (4.10)

$$P = 1.73\text{x}10^{-10}.\ Q^3 - 8.66\text{x}10^{-5}.Q^2 + 13.96.Q - 7.2 \text{ x } 10^5 \qquad (4.10)$$

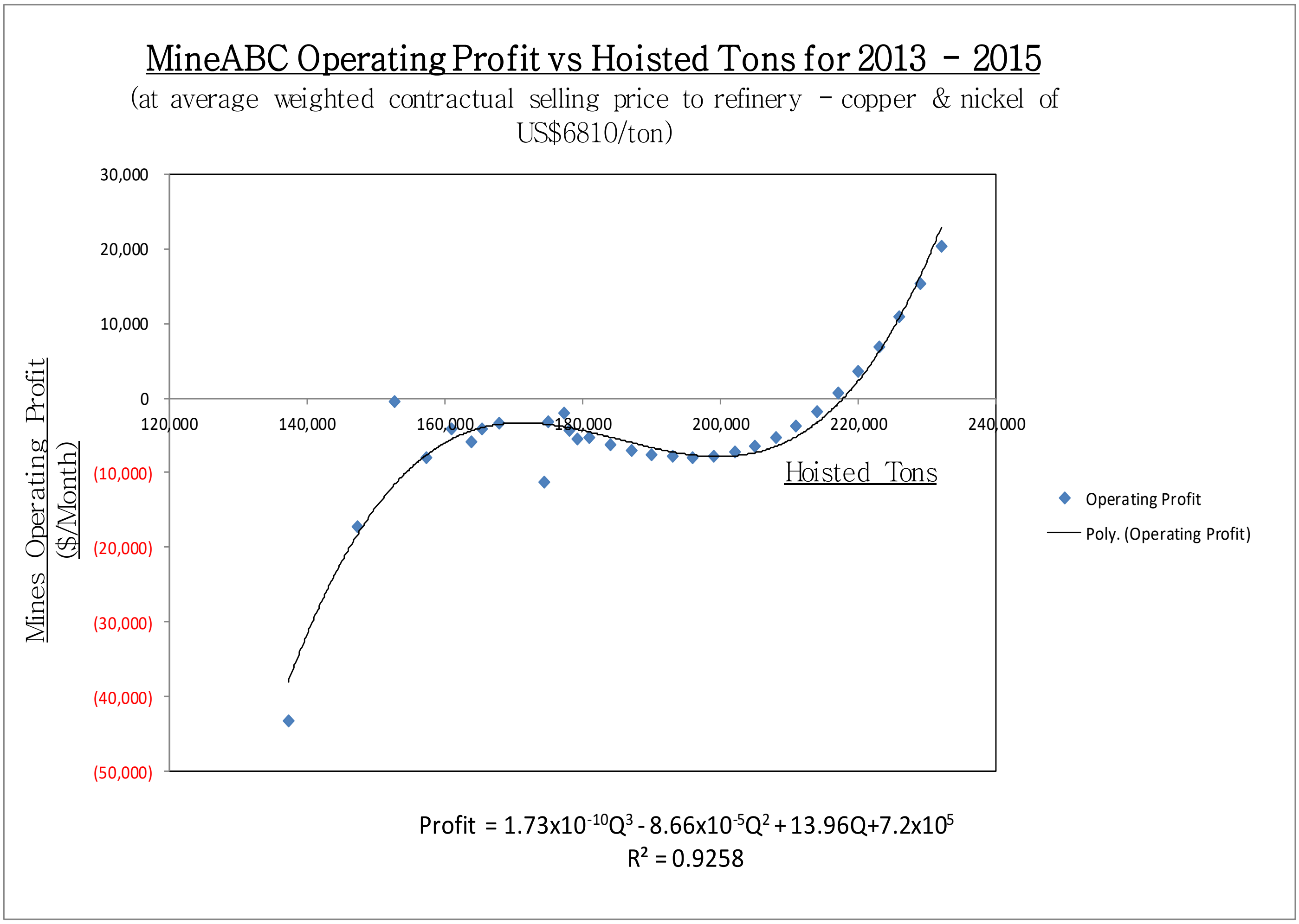


Figure 4.7 – Relationship between operating profit vs hoisted tons 2013-2015 (Source-Monthly Reports)

Figure 4.7 indicates that at operating conditions and at the prevailing price of that time, the business could only have broken even at around 218,000 tons of ore per month. The profitability of the business could increase drastically on a cubic function of the hoisted tons if production was increased beyond 218,000 tons/month. The 5-year budgeted capacity of the mine was 227,528 tons but during this period the mine was averaging only 79% of the budget (180,838).

The total hoisted tons, which is the total throughput from the mine could in this case could have been a key driver of profit up to the mine capacity limit. The budget Figure for the mine was 213,407 which means that if the mine was to produce as per budget it would still not be breaking even, hence there was need to increase hoisted tonnage to 218,000 tons.

Further gains could also have been obtained through reducing the fixed and variable mining costs. However, assuming the business could still break even at the existing prices, the maximizing of hoisted tons would be the major value driver in this case and was used for analyzing various opportunities in the business in Chapter 7.

4.4. PRODUCTION ANALYSIS FOR SYSTEM LEVEL DECISIONS

4.4.1. Overview of system understudy - MineABC ShaftA3

To do a proper value analysis of the mine production process, it was important to choose one of the shafts as a case study and analyse the production flow since the shafts were configured differently depending on the ore bodies. In this case, ShaftA3 was chosen and used in the case study as it was the biggest of the shafts in terms of ore tonnage output.

Figure 4.8 below depicts the generalized production process flow map for ShaftA3 which was budgeted to produce 75,400 tons ore per month (2,900 tons/day) from underground. The physical arrangement of the mine is shown with the four mining zones identified as Zone1, Zone2, Zone3 and Zone4. As was the case in the whole mine, ShaftA3 was also not meeting its production targets. ShaftA3 had measured, inferred and indicated resources of 33 million tons and equivalent of 180,145 tons Nickel and 155,782 tons copper contained metal.

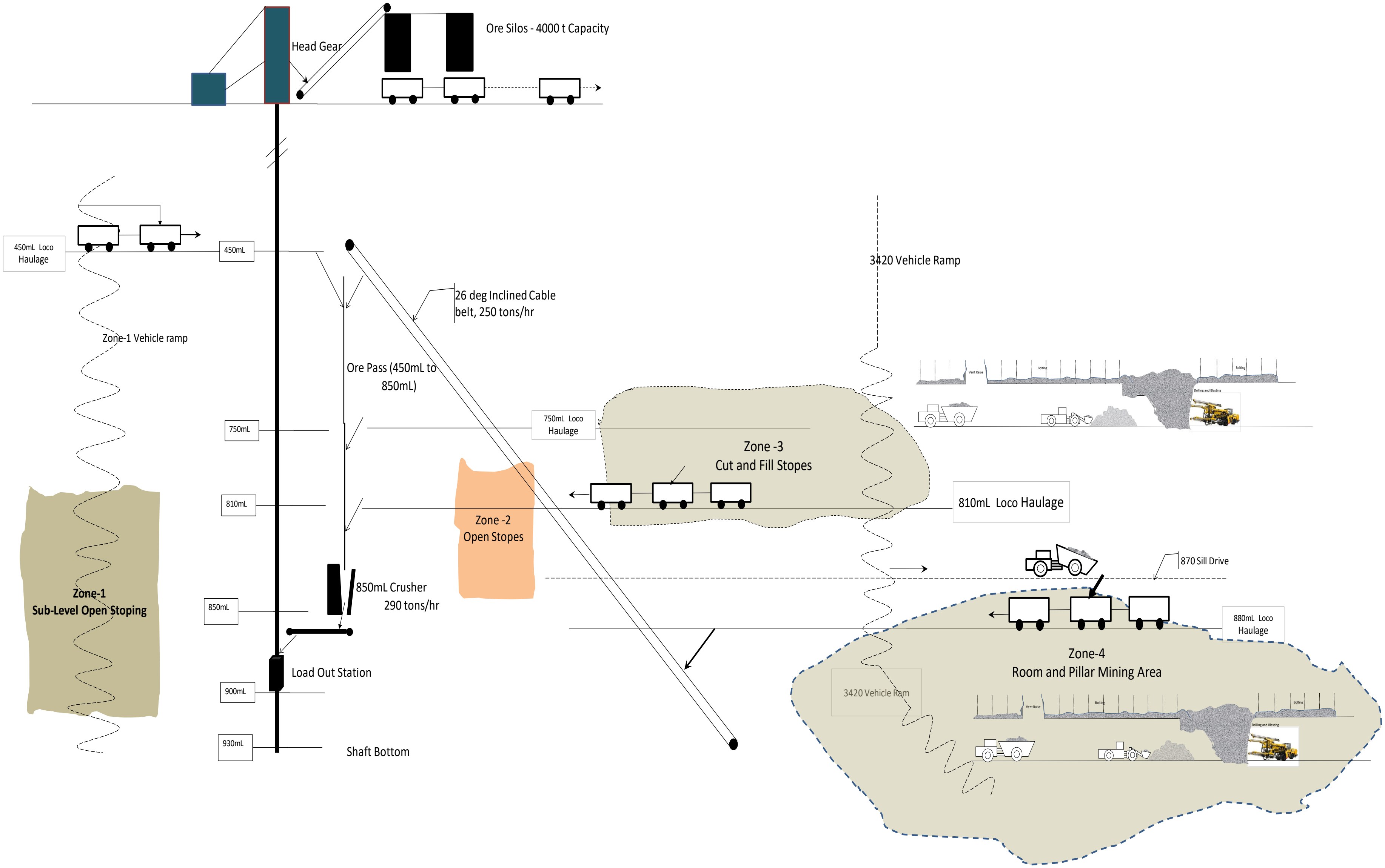


Figure 4.8 – Schematic of ShaftA3 at MineABC

The known reserves were 22.3 million tons for Zone 1, 2, 3 and 4 with a combined average grade of between 0.54 - 0.72% Nickel and 0.45 -1.07% Cu. The Sub-level open stoping, conventional stoping, cut and fill, and, room and pillar mining methods were employed in the different mining zones.

The summary of the trackless equipment and that was available capacity is as detailed below.

Monthly planned production : 75,400 tons (2,900 tons/day of ore)
Working days and shifts : 25 days, and 3 x 8hr Shifts
Diesel trackless fleet : 5 x Production drills, rated 55kW each
13 x 10-ton LHDs, rated 122kW each
6 x 20-ton UG Trucks, and 3 x 32 UG Ton Trucks
Total rated capacity of Diesel fleet – based on possible 8 loads/hr/LHD at 12 hrs/day and 26 days /month: 18,000 tons/LHD/Month x 13 LHDs x 12 months = 2,808,000 tons/year
2015 actual production : 904,800 tons/year

Drills generate ore by breaking ground. In 2015, ShaftA3 used five drill rigs to generate ground. On average, each face drill rig operated only for a total of 1.78 percussion hours per day against a target of 7.57 hours per day, which was either due to inherent constraints or excess capacity. Performance data for the drill rigs in 2015 is summarized in Appendix B3

Similarly, total tons of ore moved in 2015 by LHDs was 72% of Budget (Appendix B4). Because of the mine design, only LHDs were used to move the blasted ground, it can be said that all the ground which was moved in 2015 is what the LHDs could move. If 13 LHDs were used for production of which each LHD was averaging only moving 4419 tons/month against a target of 18000 tons per month for a 10ton LHD, which was only 25% against benchmark.

Dumptrucks were used as support to the loaders for moving the ore. Dumptrucks moved 71% of the ore transported in the system per day. LHDs moved the rest of ore straight into ore tips without dumptrucks. Each truck was averaging 2.2 loads in an hour due to various reasons such as distance to the tips as well as LHD availability. The trucks were operating at 60% of their capacity.

A production balance Figure 4.9 depicts the deficit in production between actual vs budget for year 2015 for each equipment type. Opportunities for additional 310,712 tons would have been added to the system if the factors prohibiting meeting the production targets could be rectified at the time.

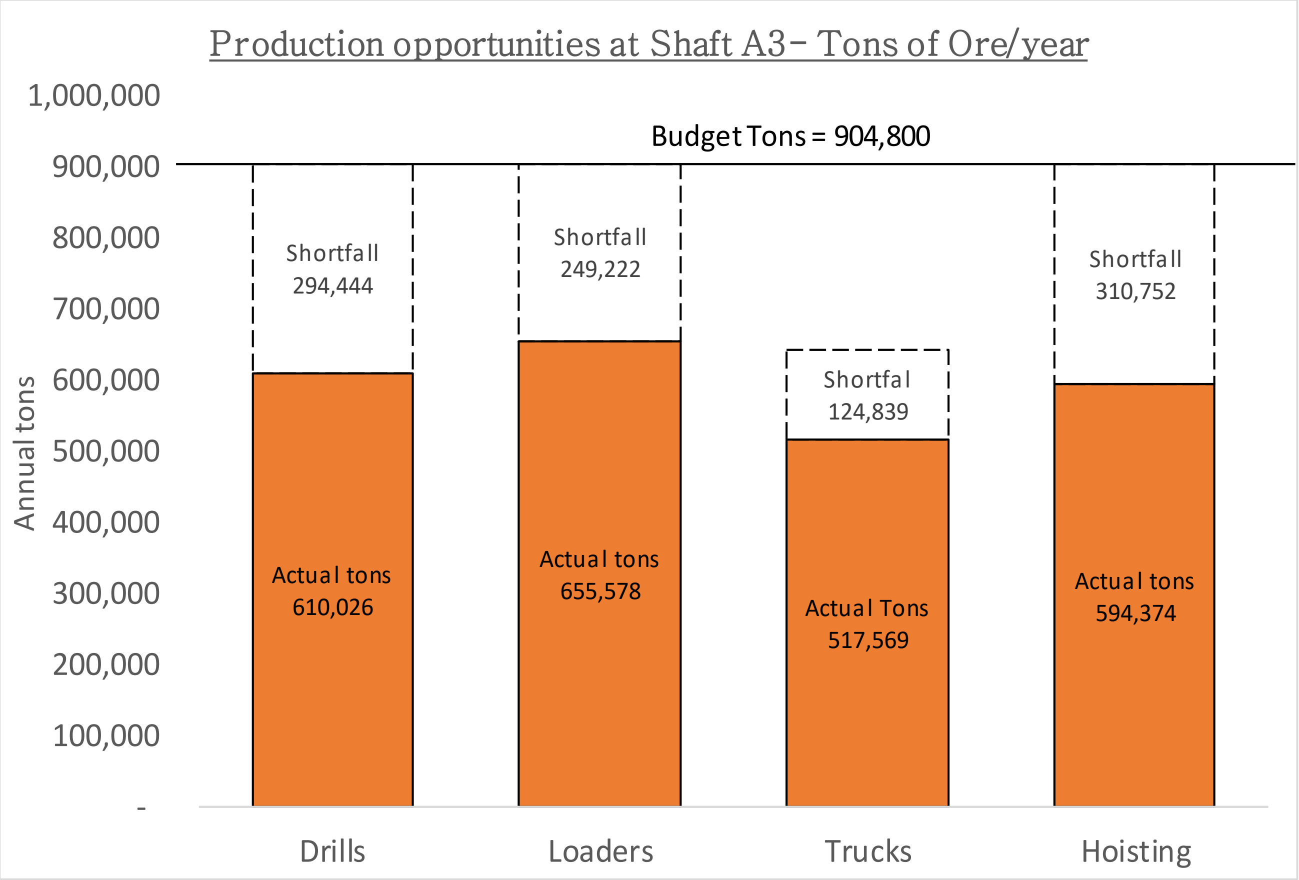


Figure 4.9 – Production opportunities at ShaftA3 – MineABC

Understanding system constraints and developing intervention and improvement strategies has proven to be one of proven business success philosophies. Through applying techniques such as value stream mapping, theory of constraints (TOC), throughput accounting (TA), linear programming (LP) and various lean techniques, it is possible to develop a system that can be used to identify process constraints and developing ways and means to debottleneck the constraint.

Theory of Constraints (TOC), Value stream mapping and Gross Cycle Time Analysis were some of the tools applied in this study to show how improved decision support systems can unlock values in an underground mine. Findings from MineABC are presented here to illustrate how these tools could be used to aid in improved decision making for value adding.

4.4.2. Theory of Constraints - Identifying system constraints at MineABC-ShaftA3

Institute of Management Accounting USA(IMA, 1999) describes that all organizations are systems made up of interdependent activities, each with its own level and type of variability. Performance can only be optimized by management understanding and focusing on the total system impact of a decision or event, not just on its local or immediate effect.

This can be done through focusing on the total system constraints because no matter how fast the other components can do their job, the system cannot produce at a rate faster than its slowest component or activity. The visibility of system constraints through a real-time system could be used as an intervention in such a situation to debottleneck the system and increase through-put.

A constraints map was developed to help identify likely bottlenecks in the 4 mining zones at ShaftA3 as illustrated in Figure 4.10. The constraints map shows that mine production system producing only at 72% of the target at 2,091 t/day versus target of 2,900 t/day. 3M mining zone was a conventional mining zone and mining zones 7M, 4M and 5M were mechanized.

The constraints map Figure 4.10 illustrates that the ore tons which was being generated by drilling and blasting in the zones 4M and 5M was already 20% below the line targets at 1,442 t/day versus 1,800 t/day combined. It therefore basically means that the mine was not generating enough ore to meet the production targets and hence was difficult to meet the production targets. 4M and 5M drilling processes were thus system constraints therefore. On the 7M mining zone using sub-level open stoping (SLOS) mining method, it can be identified that system was generating enough ore at 560 t/day above line target of 500 t/day, but the loading process was loading at 375 t/day, thereby making the loading process a constraint too.

The premise here is that if only this information was made visible and available on a real-time basis and alerts send to the relevant personnel, the loss causes could have been arrested and reversed well in time. The complexity of the production system which had 4 separate mining zones in the same shaft made it very difficult to identify areas of constraints during the run. Production loss could be greatly minimized if management had a tool to identify the constraints early.

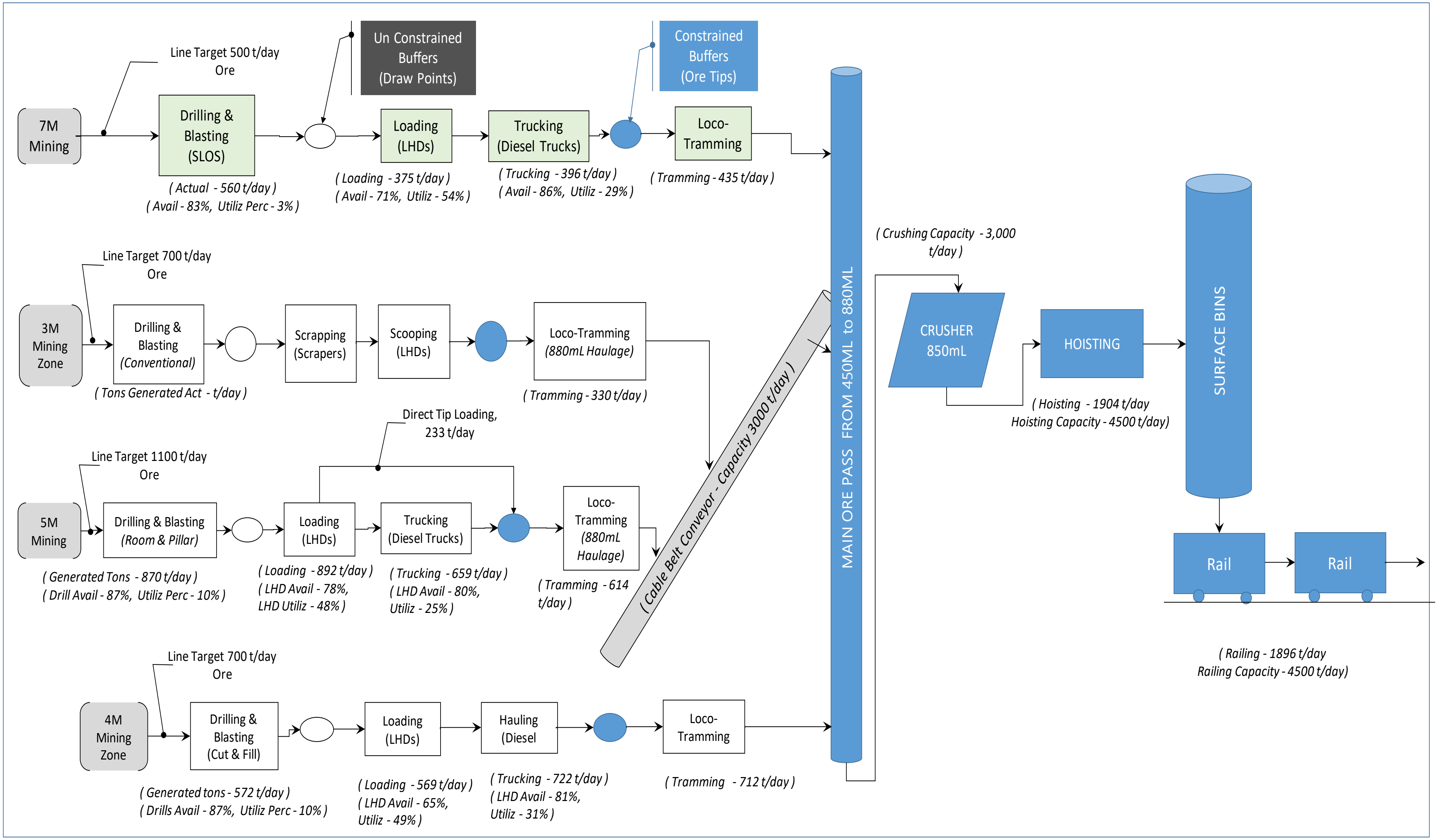


Figure 4.10 – Constraints map at ShaftA3 – MineABC

4.4.3. Value stream map - analysis of ore flow delays and residence times at ShaftA3

Another way to illustrate the constraints in the production system was to draw a value stream map of the mine production system. The value stream map will be able to illustrate the value adding and non-value adding activities which can be eliminated if they are made visible in time. This will be achieved through analysis of system delays and ore residence times at each stage of the production process.

According to the definition given in Section 2.2, a delay is a process whose output lags its input. Material delays capture the physical flow of materials through a delay process. It is a very important parameter in a production process to determine the actual capacity of the production system. In the case of a mining production, the process is normally constrained by various resources such as labour, materials, capital and other resources.

Therefore, the decision rule for determining the outflow rate of the mine needs to be formulated through understanding the stock and flow structure of the process. A stock/flow diagram for a trackless mine production flow is represented by Figure 4.11 showing the ore in transit and the delay structure.

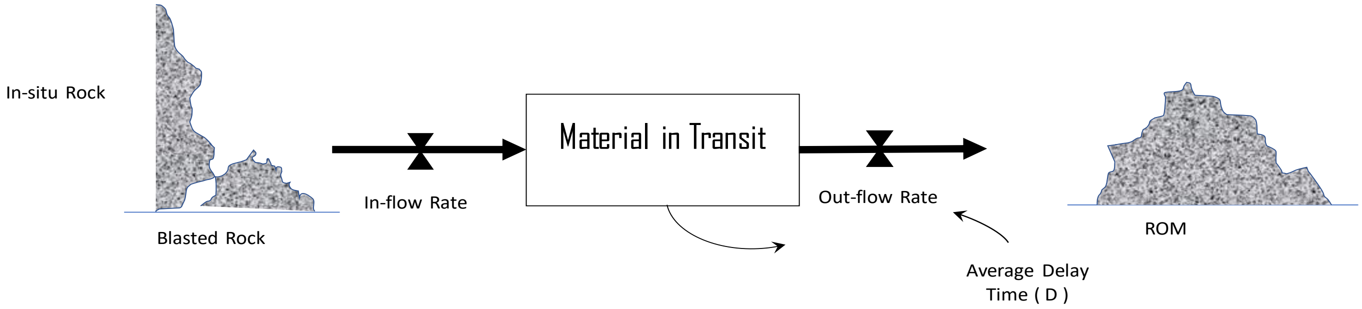


Figure 4.11 – Representation of a materials process delay structure for a trackless system

Sterman (2000), gives the formulas for outflow rate for a production system versus the residence times and show it as a function of the Stock/Material in Transit, as was given by equation (2.1) to (2.4)

$$\text{Stock, S(t)} = \int_{to}^{t}[Inflow(s) - Outflow\ (s)]ds\ + Stock(to) \qquad (2.1)$$

$$\text{d [S(t)]/dt} = \text{Inflow(t) – Outflow (t)} \qquad (2.2)$$

If D represents the average delay or residence time of the stock in the system, the outflow is given by:

Outflow = Material in Transit / Average Delay Time = $S(t)/D$ (2.3)

Or, Average Delay Time (D) = Material in Transit/Outflow (2.4)

The above formulas are used to estimate the volumes of ore in transit in relation to the total ore being sent to the ROM pads. Material in transit consists of the ore generated that day, plus the stock or work in process (WIP) already in the system, less the ore outflowing or being railed to the concentrator. To maximize the outflow, material in transit must be maximized as well as minimizing the average delay time (ore residence time) in the system.

Residence time looks at the time for broken rock to flow through the system after breaking it, until it is on surface as ROM. These parameters can be used to indicate which areas have constraints to the total output. A production flow system for a trackless mine is presented by Figure 4.12 with the circles representing buffers/temporary storage in between the different mining work stations.

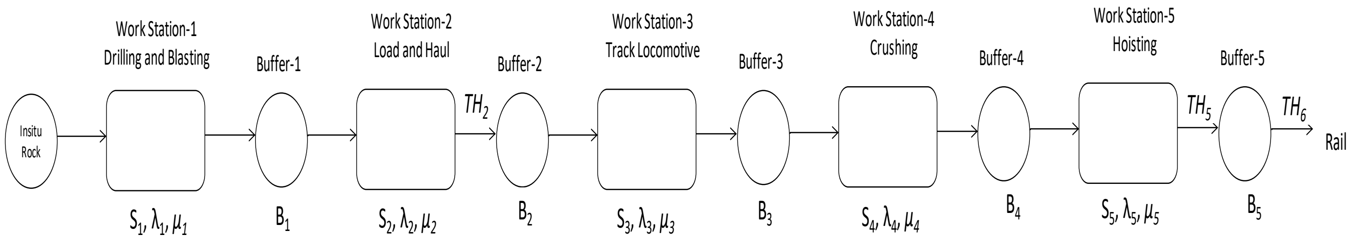


Figure 4.12 – Trackless production system flow

Data recorded from the different stages of the mining process at MineABC was analyzed for 57 days in a period of two months in 2015 using equation (2.4). The production process had six stages as: drill and blast, load and haul, tramming, conveying and crushing, hoisting and then railing. Each stage is separated by a buffer of stock in transit.

Using equation (2.4), the delay time or residence times at the different buffer stages from B1, B2, B3, B4, B5 were calculated for the 57 days where data was available. Table 4.1 summarizes the delay trends at the different stages.

Ore in Transit Analysis for 2015 at MineABC

Stage	Flow from	To	Average Daily Ore Tons in Transit	Averge Daily Ore Tons Outflow from stage	Ore-Residence Time between the stages (Days) (= Ore in Transit/Outflow)
1	Drill & Blast	Load & Haul	2416	2101	1.24
2	Load and Haul	Tramming	2362	2047	1.14
3	Tramming	Hoisting	2119	1839	1.87
4	Hoisting	Railing	1843	1803	3.70
		Total			7.95

Table 4.1 – Ore in transit analysis

Using equation (2.2) a plot of [inflow(t)-Outflow(t)] for 57 days is shown in Figure 4.13. The best fit equation for the Figure 4.13 is calculated as:

$$d[S(x)]/dx \quad = \quad -518.3\ln(x) + 2053.2 \quad = \text{Ore Inflow} - \text{Ore Outflow} \qquad (4.1)$$

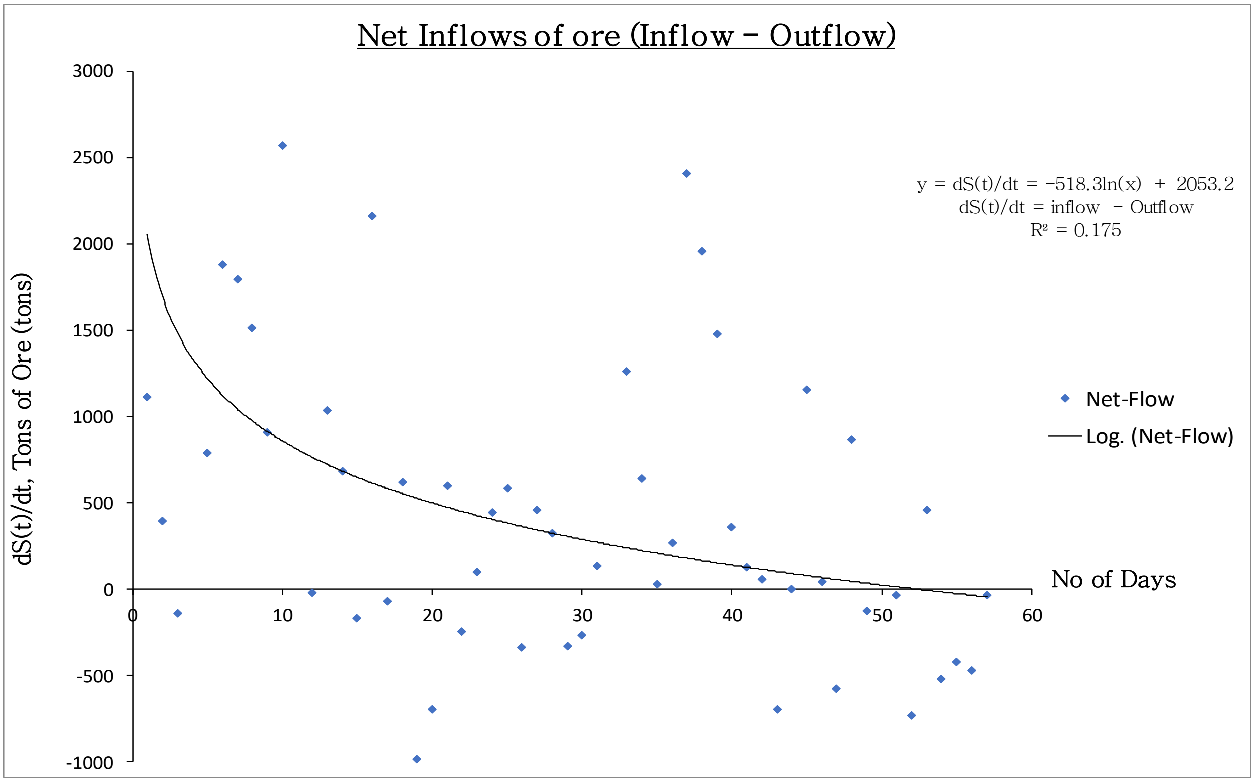


Figure 4.13 – Plot of underground stocks per day (net inflows) at MineABC – year2015

Integrating, S(t) = $\int_{to}^{t}(-518.3\ln(x) + 2053).dx$

Material in Transit, S (t) = $518.3[t - t.\ln(t)] + 2053t$ (4.2)

Using equation 4.1 and 4.2, the total production outflow (in this case railed tons/day) was plotted against the residence time using equation 4.3

Outflow (t) = Material in Transit, S(t)/Delay time (D)

Outflow (t) = $(518.3[t - t.\ln(t)] + 2053t) / D$ (4.3)

A plot of the impact of varying the process residence/delay time (D) on the total output of the mine is given by Figure 4.14 which becomes a decision chart showing the impact of varying the ore residence time in the system.

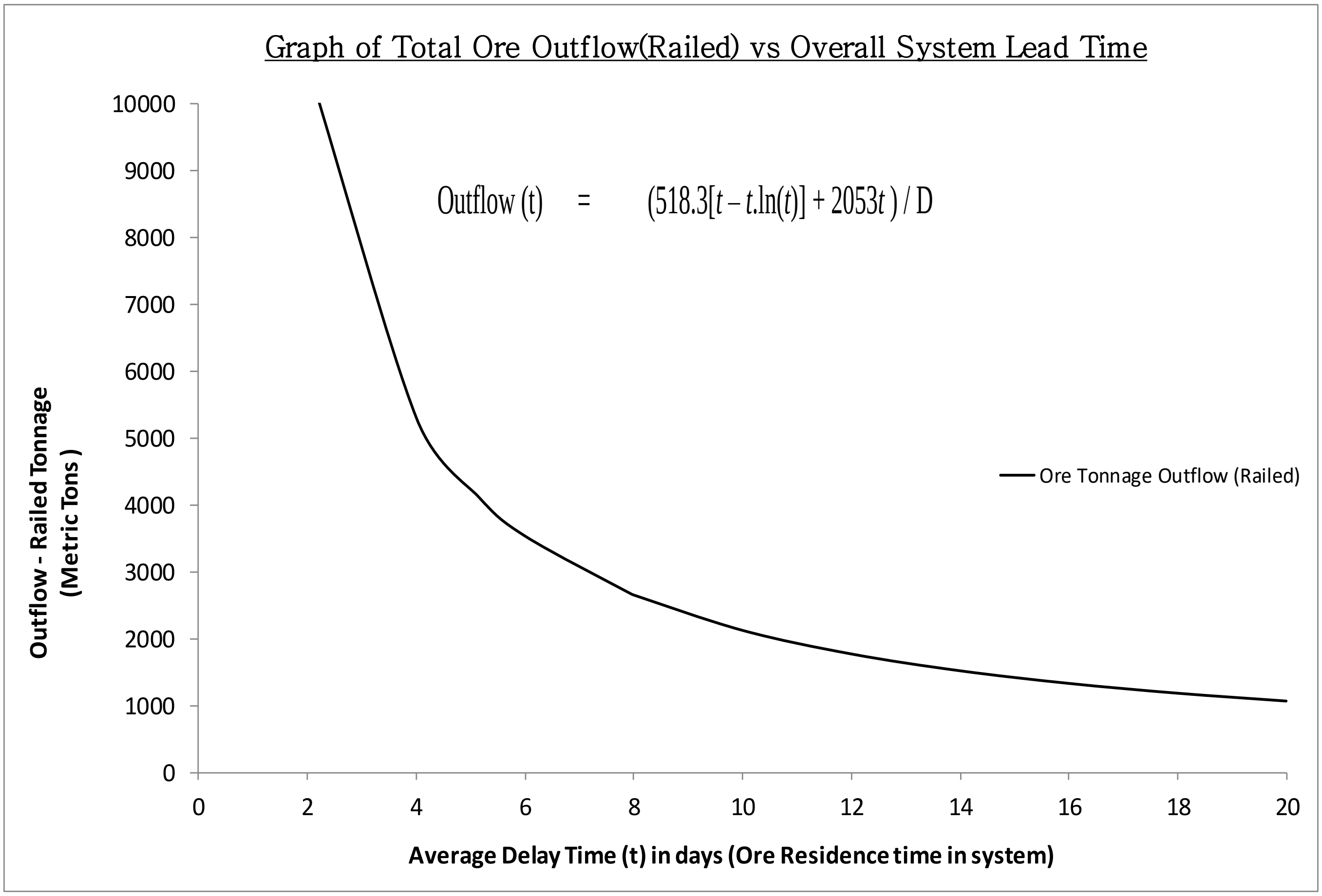


Figure 4.14 – Variation of railed tons vs ore-residence time at MineABC

Representation of the various work in process (WIP) residence times can thus be represented by a value stream map (VSM) across all the system buffers. Figure 4.15 is a value stream map of this production system used as a tool to identify the overall dynamics of the system delays at each stage of the value adding process. This illustrates the overall system delays from when the blast of ore takes place to the time the broken and crushed ore is railed to the concentrator.

Deductions from the value map Figure 4.15 includes the following:

- The system lead time was 7.95 days. That is to say it took 7.95 days x 3 shifts per day from the time drill and blast commences to the time the ore was at the ROM pad stock pile being railed to the concentrator.
- A total of 24 shifts (or 7.95 days x 3 shifts per day) was required to get the ore out of the ground which equates to 191 calender hours total time. Planned production hours per day at 20 hours per day equates to 159 hours planned operating time (20 hours/day x 7.95 days).
- Of these 159 hours operating time shifts, only 43.41 hours are actual value-add time which was 27.3 % of the operating time. The rest of the time was non-value adding.
- Table 4.1 show that the largest portion of the ore residence time was between the hoisting and railing stage of the value chain at 3.7 days. This was due to the fact that a large ore pass for the mine was designed in such a way that all the ore from the four mining zones congregated and was tipped from 450m level up and then flowed all the way down to the 850m level.
- The crushing and loading stations were at this 850m level which was the bottom level of the mine and this implied that ore could stay in the ore pass which acted as a large silo for large periods before being hoisted out. There were very little interventions which could be done to improve this as it was an infrastructure issue.
- The next possibility was to investigate how to reduce the residence time for the drill/blast cycles and the load/haul stages. In the next stage of the analysis the impact of reducing the ore residence time in the system is considered.
- The buffers, or temporary storage areas between the stations must always have enough capacity to run the next station so that the stations are not starved of the ore.

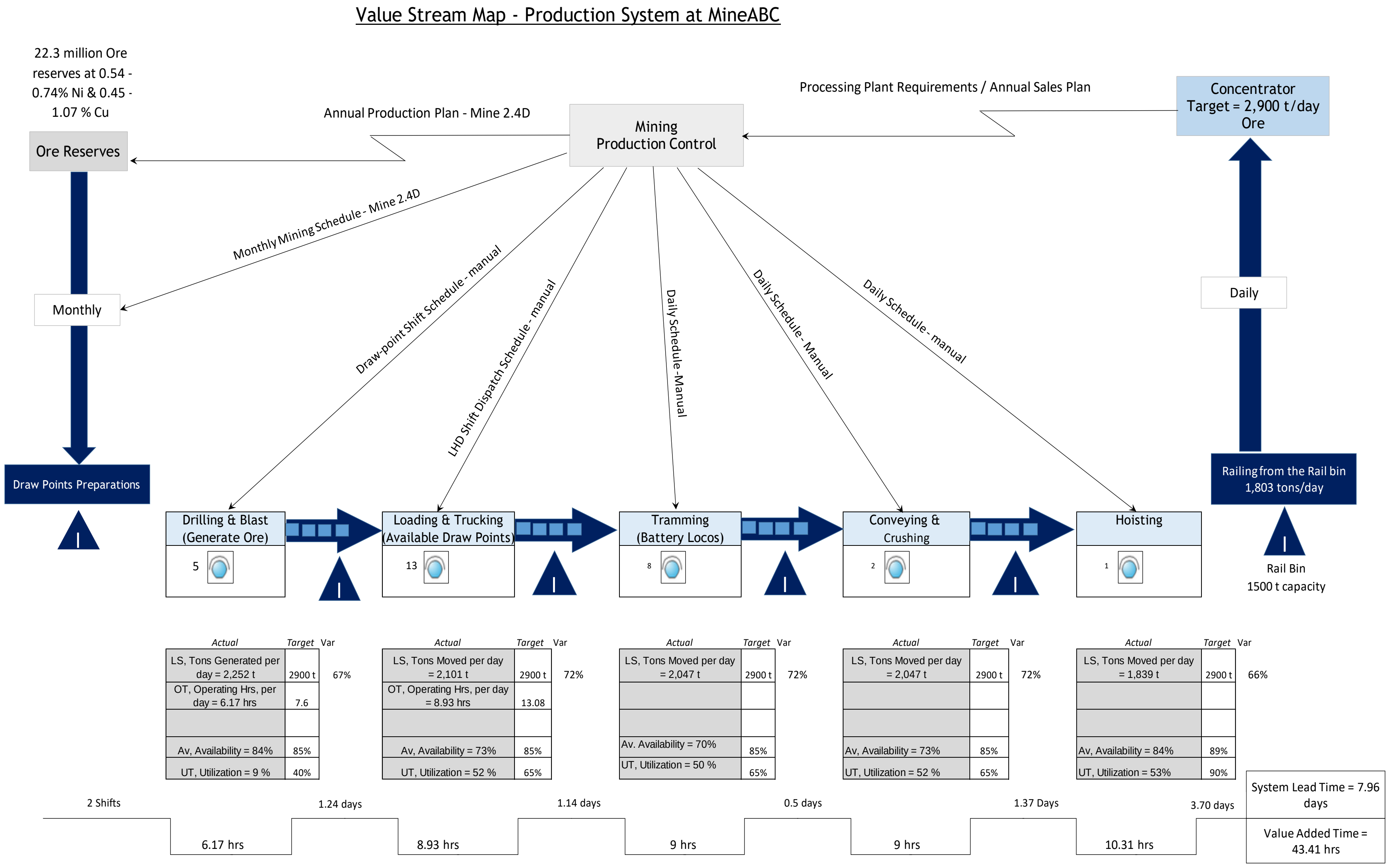
- In the analysis of the value map, it could be deduced that the drill rig were generating 2,252 tons of ore per day, which was less than the budgeted tons of 2,900 tons/day. The whole production system had no capacity to meet the targets because not enough ore was being generated per day, so the drill and blast process was also a constraint to the process.
- It could also be noticed from the VSM that the total tonnage moved each day was progressively getting less on each stage of the process. The drills generated an average of 2,252 tons/day, the LHDs moved 2,101 tons/day, Loco tramming 2047 tons/day hoisted 1,839 tons/day and railed 1,803 tons/day.
- This scenario is an indications of how the output was in general lagging behind the input and there is an indication of accummulation of the ore in the system. What was generated took time to find its way out of the system.

4.4.4. Production Line Balancing – Calculation of TAKT and Gross cycle times

The value stream analysis illustrated the overall production system delays or process lead time. However, a production line balancing technique becomes crucial to pin-point the areas which are the main bottlenecks of the production line which could be improved through better visibility of the whole process. Great improvement potential lies in the elimination of bottlenecks and excess capacities in a production process.

Due to geographical configurations, most activities in an underground operation are invisible to each other. This makes it impossible to have a smooth flow of the mining processes as they occur as cyclic batch process. The first point at creating a load balance chart is to calculate the gross cycle time at each work-station, compare it with the Takt time (TT) and then identify which areas are constrained or not.

The Takt time (TT) is the first important metric to understand in a production system. Takt time (TT) is the time required to meet the rate of demand of a product (ore in this case). Bottlenecks are the areas that have gross cycle time more than TT and excess capacity is where the gross cycle time is less than the TT.



Drilling & Blast (Generate Ore)

Actual	Target	Var
LS, Tons Generated per day = 2,252 t	2900 t	67%
OT, Operating Hrs, per day = 6.17 hrs	7.6	
Av, Availability = 84%	85%	
UT, Utilization = 9 %	40%	

Loading & Trucking (Available Draw Points)

Actual	Target	Var
LS, Tons Moved per day = 2,101 t	2900 t	72%
OT, Operating Hrs, per day = 8.93 hrs	13.08	
Av, Availability = 73%	85%	
UT, Utilization = 52 %	65%	

Tramming (Battery Locos)

Actual	Target	Var
LS, Tons Moved per day = 2,047 t	2900 t	72%
Av. Availability = 70%	85%	
UT, Utilization = 50 %	65%	

Conveying & Crushing

Actual	Target	Var
LS, Tons Moved per day = 2,047 t	2900 t	72%
Av, Availability = 73%	85%	
UT, Utilization = 52 %	65%	

Hoisting

Actual	Target	Var
LS, Tons Moved per day = 1,839 t	2900 t	66%
Av, Availability = 84%	89%	
UT, Utilization = 53%	90%	

Figure 4.15 – Value stream map for shaftA3

In a mine there is only one product family, which is the ore delivered at the stockpile called Run of Mine (ROM) and there is normally a fixed demand of the product due to the structural design of a mine.

TT – Takt time – is the rate at which the product (ore in this case) must be produced in order to meet the daily defined demand and is defined mathematically as:

$$\text{TT, } \textit{Takt time} = \frac{Available\ work\ time\ in\ the\ Period}{Average\ Demand\ in\ Period} \tag{4.4}$$

For Shaft-C at MineABC, the demand was 2,900 tons per day. The mine worked on a 3 x 8 hour shifts with 4 hours dedicated to blasting time. So, the available working time was 20 hours. There was also 6 hours dedicated to shift changes, leaving only 14hrs as actual available time. The Takt time for each station cannot be the same since different numbers of machines are used in the production at each station, so total available hours at each station must be multiplied by the number of producing units.

Using the process flow Figure 4.11, the TT was calculated for each station in this case as follows:

(1) TT for fleet of 5 x Drill rigs, budgeted effective operating time up of 14 hours per day and demand to produce 2900 tons per day is calculated as:

$$TT_{drills} = \frac{Available\ work\ time\ in\ the\ Period}{Average\ Demand\ in\ Period} = \frac{5\ x\ 15\ hours\ x\ 60\ mins}{2900\ tons} = 1.45 \text{ minutes/ton (87 secs)}$$

It means that each drill rig was to drill at a rate of 1.45 minutes/ton to meet the production demand, otherwise any less speed will result in failing to produce the required tonnage. The effective time was made up of 4 hours reserved for statutory blasting times twice a day plus travel times in each shift of 2 hours for three shifts giving 6 hours travel time.

On the same note for 13 producing loaders, TT for 14 hours available production time for each loader,

$$TT_{loaders} = \frac{Available\ work\ time\ in\ the\ Period}{Average\ Demand\ in\ Period} = \frac{13\ x\ 14\ hours\ x\ 60\ mins}{2900\ tons} = 3.76 \text{ min/ton (226 secs)}$$

For 9 trucks which are hauling 72% of total tonnage, TT for 14 hours available production time for each truck to haul 2,088 tons/day (72% x 2900 tons), the balance of the tons (812 tons) are moved directly by LHDs into tips daily

$$TT_{trucks} = \frac{Available\ work\ time\ in\ the\ Period}{Average\ Demand\ in\ Period} = \frac{9\ x\ 14\ hours\ x\ 60\ mins}{2088\ tons} = 2.60 \text{ min/ton (156 secs)}$$

The next important factor is to calculate the gross cycle time at each work-station. The gross cycle time is determined through considering the effects of net process cycle time (CT_{net}), changeover times (CT_{co}), uptime restriction due to equipment and process availability (CT_{up}) and the quality losses time (CT_Q) which are defined below.

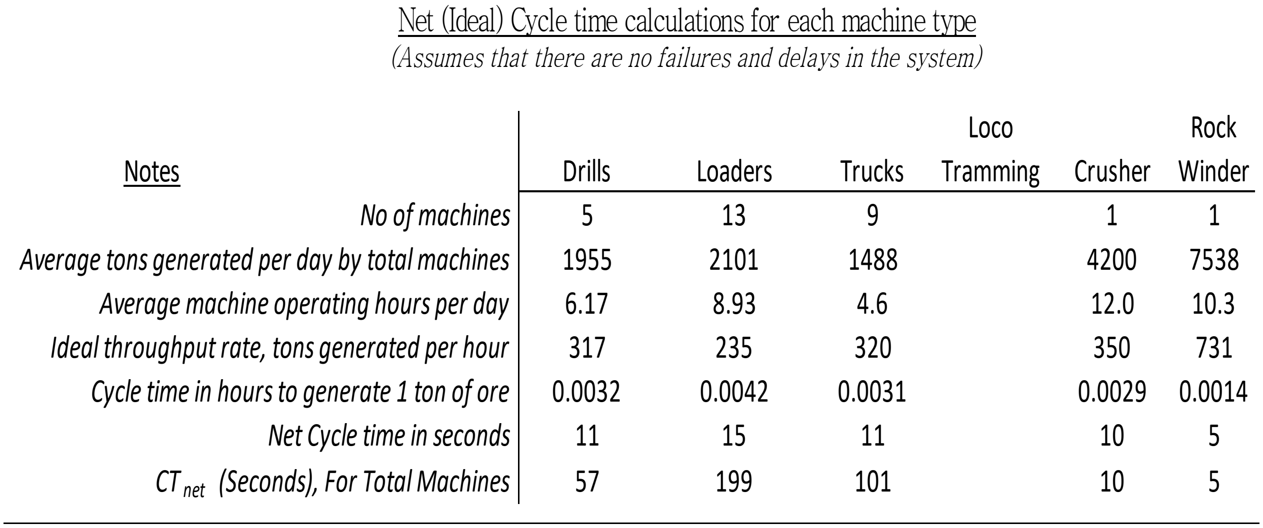
- CT_{net} – is the ideal cycle time which is only achievable in ideal conditions

$$CT_{net} = \text{Net cycle time per station} = \frac{1}{PS} \tag{4.5}$$

Where, PS is ideal station throughput rate

There was a total of 5 drills generating 2,252 tons of ore per day over an average of 6.17 operating hours per day. Number of loaders was 13 loaders, generating 2101 tons of ore per day operating average 8.93 hours per day. 9 trucks moved 1488 tons per day operating only 4.6 hours per day. Trucks only moved 75% of the ore, the rest was tipped straight by loaders into tips. The crusher and the winder operated for 12 hours and 10.3 hours respectively and these had excess capacity of doing 4,200 tons/day for the crusher and 7,538 tons/day for the rock winder.

The different net cycle times CT_{net} for each type of equipment was calculated as follows using information in Table 4.2 and from details of each machine type found in Appendix B



Net (Ideal) Cycle time calculations for each machine type

(Assumes that there are no failures and delays in the system)

Notes	Drills	Loaders	Trucks	Loco Tramming	Crusher	Rock Winder
No of machines	5	13	9		1	1
Average tons generated per day by total machines	1955	2101	1488		4200	7538
Average machine operating hours per day	6.17	8.93	4.6		12.0	10.3
Ideal throughput rate, tons generated per hour	317	235	320		350	731
Cycle time in hours to generate 1 ton of ore	0.0032	0.0042	0.0031		0.0029	0.0014
Net Cycle time in seconds	11	15	11		10	5
CT_{net} (Seconds), For Total Machines	57	199	101		10	5

Table 4.2 – Calculations of Net (Ideal) Cycle Times for different machine types

- CT_{co} – is the extra time required for changeovers time the machine is unavailable for production due to tools change, operator and work-area changeovers such as moving a rig from one face to another

$$CT_{co} = \text{Time losses through changeover} = CT_{net} \times \frac{CO}{OT} \tag{4.6}$$

Where, OT Operating time [time unit]

CO Changeover time [time unit]

Changeover time for the drills was 6.9 hours, 4.8 hours for loaders, 5.4 hours for trucks, 6 hours for crushers and 0.6 hours for winders. Winders were doing hot seat changeover and there was never a time when there was no winder driver in a 24-hour period. Therefore, CT_{co} for each machine is calculated as;

CT_{co} (drills) = 57 x (6.9/6.17) = 64 (sec)

CT_{co} (loaders) = 199 x (4.8/8.93) = 107 (sec)

CT_{co} (trucks) = 101 x (5.4/4.6) = 118 (sec)

CT_{co} (crusher) = 21 x (6/12) = 12 (sec)

CT_{co} (rock winder) = 19 x (1/10.3) = 1(sec)

- CT_{up} – the time loss resulting from machines breakdowns and is calculated by converting the restricted uptime into a percentage of customer Takt time. Uptime refers to the entire working time of the machines

$$CT_{up} = \text{Time losses through breakdown} = TT \times (1 - UP) \quad (4.7)$$

Where, TT customer Takt time [time unit/Lot size]

UP uptime [%]

Uptime Figures for machines were as follows: Drills 86%, Loaders at 73%, crusher 98% and winders 84% availability. Therefore, CT_{up} for each machine were calculated as follows:

CT_{up} (drills) = 87 x (1 – 86%) = 12 (sec)

CT_{up} (loaders) = 226 x (1 – 73%) = 61 (sec)

CT_{up} (trucks) = 220 x (1 – 83%) = 37 (sec)

CT_{up} (crusher) = 17 x (1 – 98%) = 0.3 (sec)

CT_{up} (rock winder) = 17 x (1 – 84%) = 3 (sec)

- CT_Q – the additional time needed on grounds of quality problems or rework, rejection, low bucket fill factors, etc.

  $$CT_Q = \text{Time losses through quality defects} = CT_{net} \times QL \quad (4.8)$$

  Where, QL = quality factor

Quality factors for each type are: for drills average hole length of 3.67 metres instead of 4.0 metres giving a quality factor of 8%, loader bucket factor of 6.5 tons versus 10 ton rated which is 35%, truck quality factor of 43% based on 17 tons actual instead of rated 30 ton, 2% on crusher due to boulders and 17% on rock winders.

CT_Q (drills) = 57 x 8% = 5 (sec)

CT_Q (loaders) = 199 x 35% = 70 (sec)

CT_Q (trucks) =101 x 43% = 44 (sec)

CT_Q (crusher) = 21 x 2% = 0 (sec)

CT_Q (rock winder) =19 x 17% = 70 (sec)

The Gross cycle time (CT_{gross}), is determined by adding the three types of time losses to the net cycle time to give for each equipment type.

$$CT_{gross} = CT_{net} + CT_{co} + CT_{up} + CT_{Q} \tag{4.9}$$

Table 4.3 show the gross cycle times for each work station. This is calculated by adding the various cycle times at each work station.

	Drill & Blast	Loading	Hauling	Tramming	Crushing	Hoisting
Takt Time, TT (seconds)	87	226	220		17	17
Cycle time, CT_{net} (Seconds)	57	199	101		10	5
Changeover time, CT_{CO} (Seconds)	64	107	117		4	0
Breakdown time, CT_{UP} (Seconds)	12	61	37		0.3	3
Quality time factor, CT_{Q} (Seconds)	5	70	44		0.2	1
Gross cycle time, CT_{gross} (seconds)	137	437	300		15	9

Table 4.3 – Table of time losses in production (changeover, uptime restrictions and quality)

The information from Table 4.3 is then plotted into a load balance chart Figure 4.16 illustrating areas with bottlenecks and those with extra capacity. The load balance chart show that the drill & blast process had a gross cycle time 137 seconds versus a Takt time of 87 seconds. Inorder to meet the production budget in terms of drilling, it required that each ton of ore be produced at a rate of 87 seconds, but this was being exceeded. This meant therefore that the drilling process was a bottleneck to the production process.

Similarly, the gross cycle time for loading process was 437 seconds versus TT of 226 and for truck hauling process it was 300 seconds versus TT of 220 seconds. These two processes were therefore bottlenecks as well due to the TT being lower than the gross cycle time. However the crushing and hoisting operations had excess capacity as the TT was larger than the gross cycle times.

Since the loading process is at the core of the mining process, the next Section 4.5, is focusing on the mine loaders to analyse how the constraints can be improved be a detailed analysis of the cycle times and reliability at the loading stations.

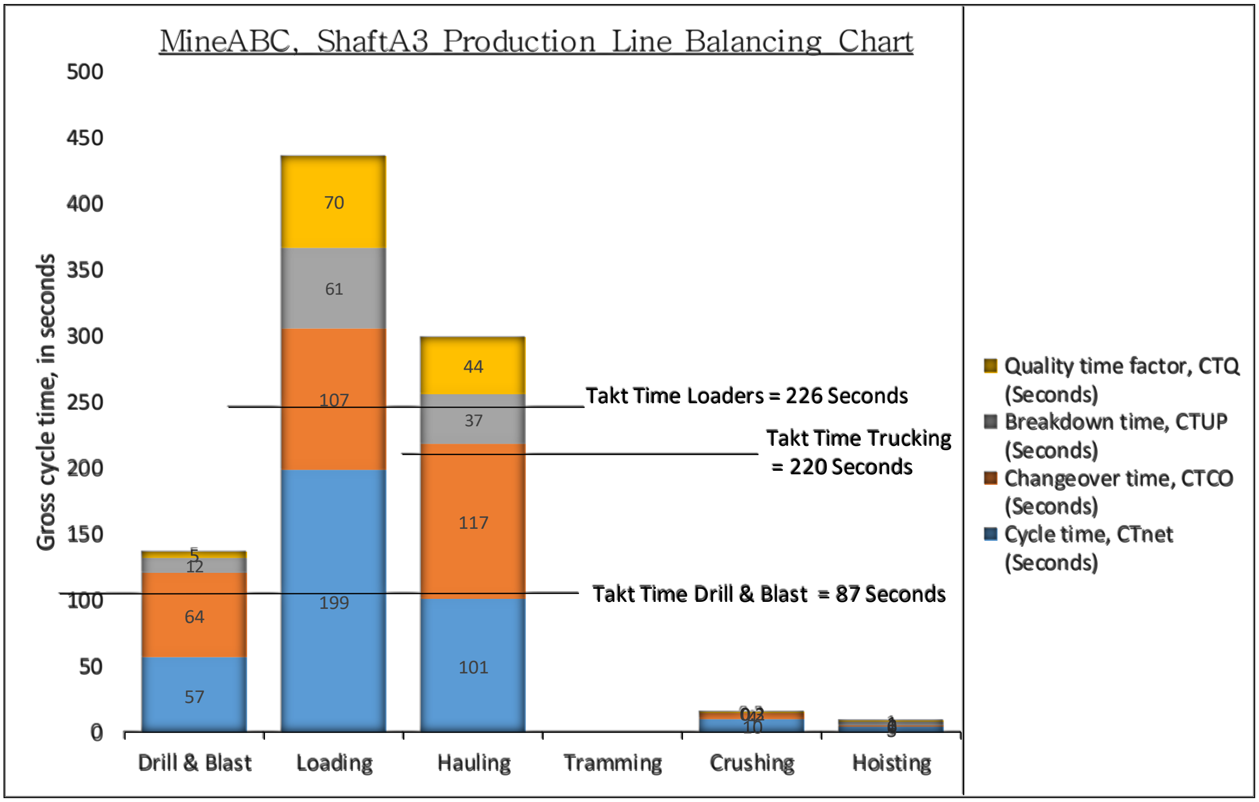


Figure 4.16 – Load balance Chart gross cycle time (changeover, uptime restrictions and quality)

4.5. WORK STATION TECHNICAL FACTORS FOR IMPROVED PRODUCTION RATE

The previous section 4.4 illustrates decisions which could be made at system level of the production process. This section illustrates decisions which can be made which have impact at work station and equipment level.

4.5.1. Decision factors which impact work station throughput rate

From the value driver tree, the hoisted tons represent the total throughput from the mining production system, called Run-Of-Mine (ROM). If we assume that the total throughput from the mining production was largely influenced by the performance of the trackless stations 1 and 2, then a two-station production line model below may be used for analysis, consisting of the drill and blast station plus the load and haul station based on Alden, et al., (2006) and Blumenfeld & Li (2005).

The serial production system illustrated in Figure 4.11 can be re-modeled into a two-station system as illustrated in Figure 4.17 for easier mathematical manipulation. The two-station to be modelled are the drill and blast, and the load and haul stations.

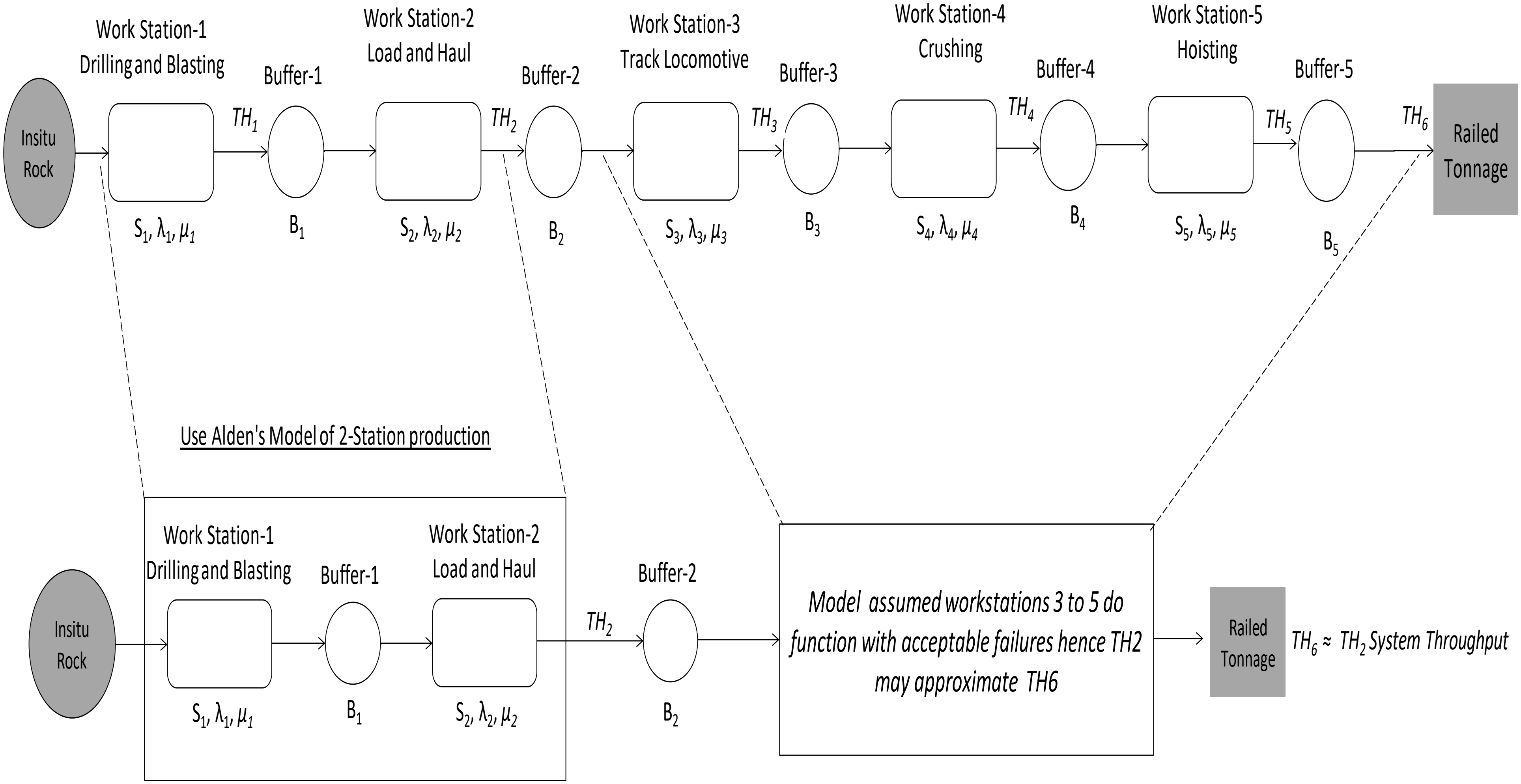


Figure 4.17 – Two station model – for trackless system with buffers

The reason for using the two station model at the drill and blast, and the load and haul stations was due to the fact that the crushing station and the hoisting stations had excess capacity and were more or less unconstrained in this production system. The actual capacity of the crusher was 4,200 tons/day at 98% availability operating 12 hours per day and actual capacity for hoisting for the rock winder was 7,538 tons/day at 84% availability and 10.3 operating hours per day. This was far greater than the actual capacity of the loaders at 2,101 tons per day (see Figure 4.15).

Therefore, using Alden, et al., (2006)'s, for a two-station model representing two work stations arranged in series and connected by a buffer, the following assumptions were made:

(a) The buffer station-1 did not fail, and ore flow through it with zero transit time.

(b) A station did not fail if it is blocked or starved (subject to failure only when operating).

(c) Operating times between failures at a station were exponentially distributed (with mean $1/\lambda_i$, i=1,2).

(d) Repair times at a station were exponentially distributed (with mean $1/\mu_i$, i=1,2).

(e)The first station (drill and blast) was never starved, i.e., there was always enough insitu rock to break; and the second (load and haul) station was never blocked, so that there were no external impediments to the line's operation. This assumption ensures that the analysis determines the maximum tonnage that could flow through the line. The equations derived for the two-station model also require the following assumption.

(f) While one station is down, the other station does not fail, but its speed is reduced to its normal speed multiplied by its stand-alone availability

Based on these assumption, the following throughput of the production line after the load and haul, TH_2 in tons/h is given by the equation (3.13) as given in previous chapter:

$$TH_2 \text{ (loads/h)} = PS\left(\frac{1}{1+2(\lambda/\mu)}\right)\left(1+\frac{(\lambda/\mu)(B\mu/S)}{2+(1+\lambda/\mu)(B\mu/S)}\right) \qquad (3.13)$$

This can also be re-arranged in relation to the availability index ($\frac{\mu}{\mu+\lambda}$) as:

$$TH_2 \text{ (loads/h)} = PS\left(\frac{\mu}{\mu+2\lambda}\right).\left(\frac{2+(\lambda+\mu)/\mu)(B\mu/S)+(\lambda/\mu)(B\mu/S)}{2+((\mu+\lambda)/\mu)(B\mu/S)}\right) \qquad (4.10)$$

Where, $\lambda_1 = \lambda_2 = \lambda$, $\mu_1 = \mu_2 = \mu$, and $PS_1 = PS_2 = PS$

4.5.2. Decisions on Loaders (LHDs) Throughput vs Avail-Index (μ/(λ+μ)

4.5.2.1. Loaders(LHDs) technical performance in 2015

Analysis of the MineABC production system showed that the total production coming out of the mine can be reasonably assumed as equivalent to the total tons moved by the LHDs (Load Haul Dumpers) or Scoops. It was only the LHDs which transferred the blasted rock from the stopes, either directly into tips or through dumptrucks again into ore tips. The ore is the trammed by either locomotives or conveyor belts into crushers and then to the hoist skips out of the mine.

The availability index, μ/(λ+μ), is the fraction of time that the LHD station is assumed available for processing the ore if never blocked or starved. During processing, some of the ore is stored in buffers such as draw points, but this is only temporarily. It could thus be seen and concluded that all tons out of the mine were the total tons moved by the LHDs.

The analysis below looks at how decisions which improve the MTBF through reducing the failure rate and reducing the MTTR through improving the repair rate could have impact of throughput and costs. The availability index trend for the underground loaders (LHDs) for MineABC for the full 2015 year is indicated in Figure 4.18. The Figure was steady between 0.7 and 0.85 even over short-term intervals and the mean at 0.77. This also implies that improvements in MTBF and MTTR may not be so easy to achieve but the analysis will look at how each gain improves plant throughput.

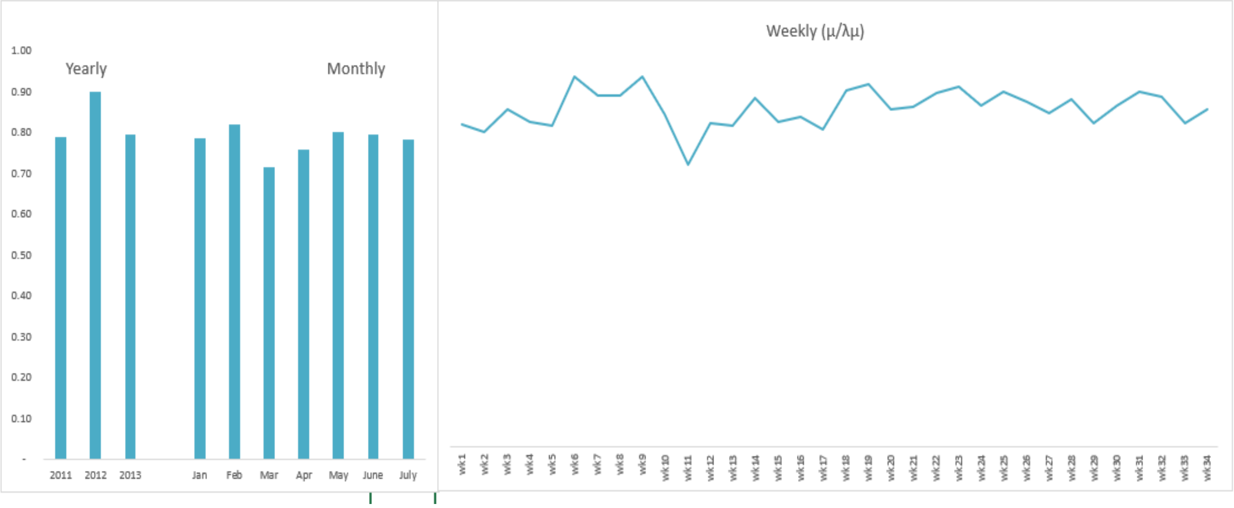


Figure 4.18 – Loaders (LHDs) availability index trends

The data for the failure rates (λ), repair rates (μ) and equipment costs/hr. are indicated in Table 4.4. This data is given in relation to the life-time age of the equipment.

MineABC Underground Loaders Reliability & Costs Data - Yr2015

Equipment ID	Max of LifeTimeHrs	Average of Failure Rate (λ)	Average of Repair rate (μ)	Average of Availability Index (μ/(μ + λ))	Sum of MthCosts (US$)	Average of Actual Run Hours	Average of Cost/Hr (US$)
BE160006	19326	0.06	0.29	0.79	401,542.95	59.43	241.5
BE160007	16845	0.09	0.25	0.74	333,758.18	60.20	193.8
BE160008	11144	0.08	0.28	0.75	465,941.54	51.53	479.8
BE160009	7188	0.09	0.25	0.75	304,669.82	43.65	670.3
BE160010	5378	0.06	0.32	0.81	482,442.67	52.68	288.5
BT30020	29986	0.04	0.41	0.88	520,818.50	51.53	276.7
BT30021	20783	0.05	0.45	0.85	291,017.43	48.33	165.8
BT30022	35601	0.07	0.23	0.74	504,775.69	62.37	239.5
BT30023	29704	0.07	0.29	0.78	322,253.56	53.80	297.7
BT30024	22630	0.04	0.32	0.86	327,879.83	46.47	347.5
BT30025	26125	0.04	0.41	0.88	304,196.51	46.03	271.0
BT40011	45836	0.06	0.32	0.83	381,796.68	48.80	431.4
BT40012	52538	0.41	0.05	0.13	72,088.10	53.33	173.9
BT40016	48000	0.06	0.28	0.79	291,365.27	53.06	124.8
BT40018	40194	0.06	0.31	0.81	291,581.71	55.60	176.2
BT40020	28479	0.18	0.16	0.53	316,228.78	61.61	220.9
BT40023	29706	0.06	0.24	0.77	433,375.83	52.31	361.1
BT40024	13768	0.05	0.33	0.85	466,706.38	51.21	302.8
BT40025	9485	0.06	0.39	0.83	356,531.37	55.03	174.9
BT40026	5094	0.07	0.22	0.70	293,879.09	52.84	140.8
BT40027	6255	0.08	0.22	0.67	331,514.20	59.67	228.0
Grand Total	**52538**	**0.07**	**0.29**	**0.77**	**US$7,494,364.08**	**53.53**	**US$271.26**

Table 4.4 – Loaders (LHDs) lifetime age, availability index and maintenance costs

Three decision areas were looked at in relation to the variation of throughputs and the availability index (μ/(λ+μ)) based on the 2015 equipment performance data summarized in Table 4.4. The first analysis considered how throughput can be varied at the same availability index. Second analysis consider the impact of varying the failure rate *(λ)* and its impact on throughput *TH*. The third analysis is on how the variation in MTTR and repair rates (μ) affects throughputs.

4.5.2.2. Loaders(LHDs) cycle time improvements (at same Availability - μ/(λ+μ))

A plot of 936 data points of LHDs throughput in loads scooped per hour (TH) over a one-year period of 2015, versus the measure of availability of each station (μ/(λ+μ)) was done for LHDs at MineABC, giving the following Figure as given in Figure 4.19.

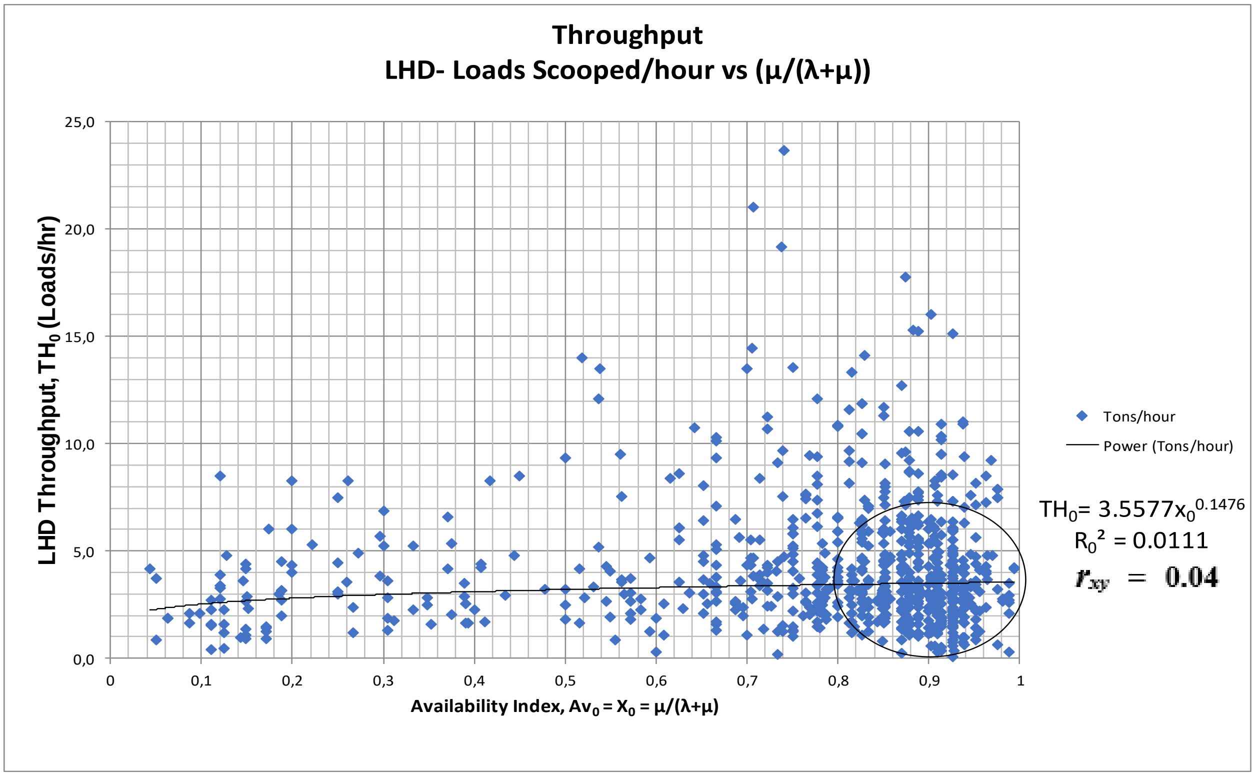


Figure 4.19 – Throughput vs Availability Index Figure at MineABC

The Figure show that "As-Is" LHD throughput was concentrated below 5 loads/h. per LHD and availability index of between 0.78 and 0.90. Best fit power trend line plot gave an equation of throughput, TH_0 at the load and haul stations as:

$$TH_0 = 3.5577(x_o)^{0.1476} \qquad (4.11)$$

Where, (x_0) represents the availability index.

A point to note is that the **Correlation coefficient, r_{xy} = 0.04** and the ***Coefficient of Determination, R^2* = 0.011** of the graph are very low, an indication of no relationship between the availability of equipment and mine throughputs. This poor correlation may thus represents a weak process where plant availability has no influence on mine throughputs and might thus be a sign of a process out of control. Figure 4.18 gives opportunity to two areas for possible interventions which could be made to the *MineABC* production system to increase throughput:

Firstly, increasing the loads per hour for each LHD at the same failure and repair rates is a highly practical possibility and could increase throughput immediately. This is highly possible as the spread of TH_0 at $\mu/(\lambda+\mu)$ of between 0.78 and 0.9 is 40% above TH_0 of 5 loads/h. So a closer look at why LHDs are performing at below 5-loads/hr. could have given an immediate impact to the production of the mine.

This could possibly have been done by improving each LHD's cycle time through looking at factors impacting the cycle time such as the LHDs tipping distances, the operator habits, roadways conditions, etc. Better mine planning and real-time operational control could have given better visibility of this activity for making better value adding decision. Figure 4.18 thus illustrates the improving potential which can come through cycle time improvements.

The following analysis justifies how cycle time improvements can be done. From equation (4.5) the ideal station rated capacity (S) is related to the cycle time (CT) by:

$$\text{Cycle time, CT} = \frac{1}{PS}, \quad \text{PS = station rated capacity} \tag{4.5}$$

PS is an ideal station throughput. The actual station throughput, given by TH is then found by multiplying with the availability index to get the actual capacity as given by equation 3.9

$$\text{Throughput, } TH = (\text{Availability x PS}) \tag{3.9}$$

The station throughput considering availability index of the station can then be related to the cycle time as follows:

From equation (4.5), $PS = 1/CT$ (4.12)

From equation (3.9) TH = Constant x PS, if availability is constant

It follows therefore that, If station availability index, $\mu/(\lambda+\mu)$ can be fixed, then the throughput can be written as

$$TH = K_c.\left(\frac{1}{CT}\right) \tag{4.13}$$

$$\text{Where } K_c = \left(\frac{\mu}{\mu+2\lambda}\right).\left(\frac{2+(\lambda+\mu)/\mu)(B\mu/S)+(\lambda/\mu)(B\mu/S)}{2+((\mu+\lambda)/\mu)(B\mu/S)}\right) \tag{4.14}$$

From the two-station production line equation (4.10).

Equation (4.13) can thus be plotted at the current λ = 0.007 (MTBF =14.3hrs) and μ = 0.29 (MTTR = 3.45 hrs.). The factor B/S can be assumed to be 1 by ensuring that the buffer is at least equal to the size of the speed rate PS to prevent any build-up. Kc becomes

$$K_c = \left(\frac{\mu}{\mu+2\lambda}\right).\left(\frac{2+2\lambda+\mu)}{2+\mu+\lambda}\right) \quad = 0.957 \qquad (4.15)$$

The plotting of equation (4.13) at λ = 0.007 and μ = 0.29 is illustrated by Figure 4.20. Figure 4.20 illustrates that at the same index of availability index of 0.806, and station constant K_c of 0.957, the loaders throughput could be improved drastically by just improving the loader cycle times.

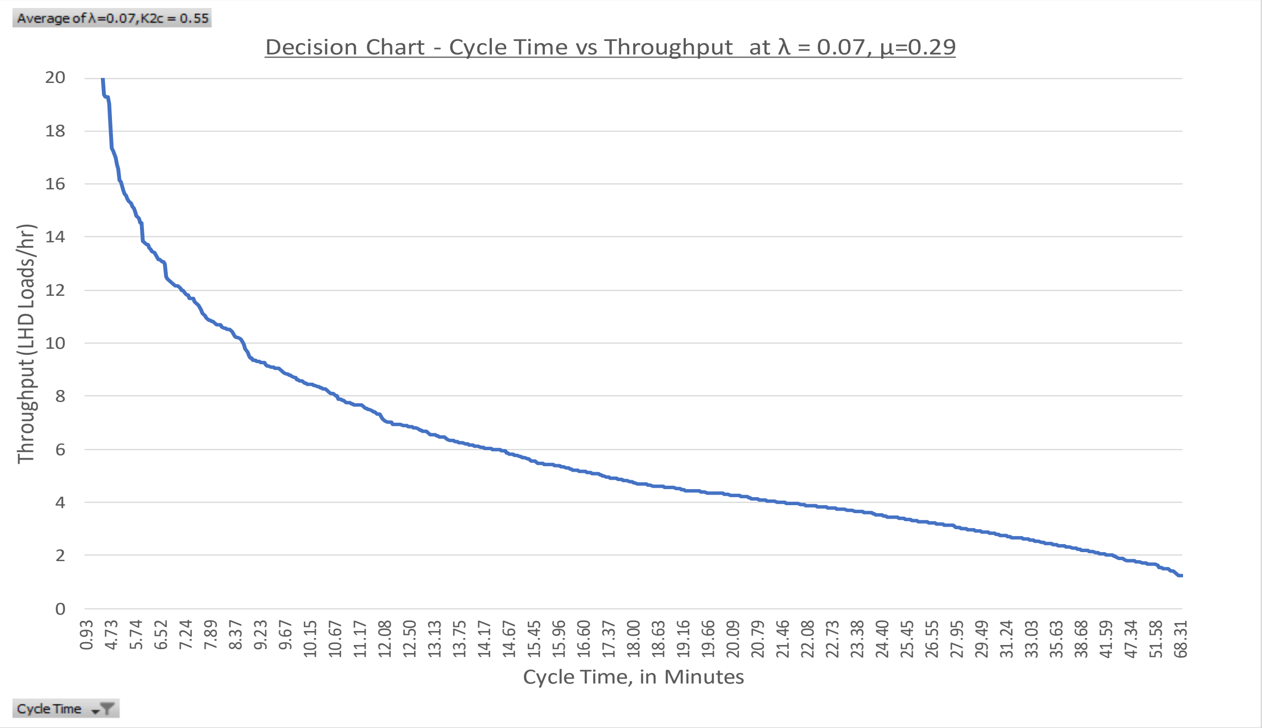


Figure 4.20 – Decision Chart - Throughput vs cycle times at fixed availability index

Based on the reasoning above, if all ***outlier data points*** between the quadrant X = 0.6 – 1.0 and, TH = 0 – 5 loads/hr .in Figure 4.19 are eliminated, a new Figure 4.21 is created. These points eliminated show all those LHDs which were operating at high availability above 60% but still were producing at less than 5 loads in an hour. This can be very low throughput for an LHD. The new equation created is represented by equation(4.16),

$$\mathbf{y = 7.535x^{0.6049}} \tag{4.16}$$

A new Figure 4.21 is created and show an upward shift which can be used as a decision chart to estimate potential tonnage improvements due to cycle time improvements.

The graph shows a marked improvement in the **Correlation coefficient, r_{xy} from 0.04 to 0.52** and the ***Coefficient of Determination, R^2*** from **0.0111** to **0.462**. Based on assumptions, the result of the improved **r_{xy} and R^2** is an indicator of the influence of the independent variable (availability) on the dependent variable (mine throughput).

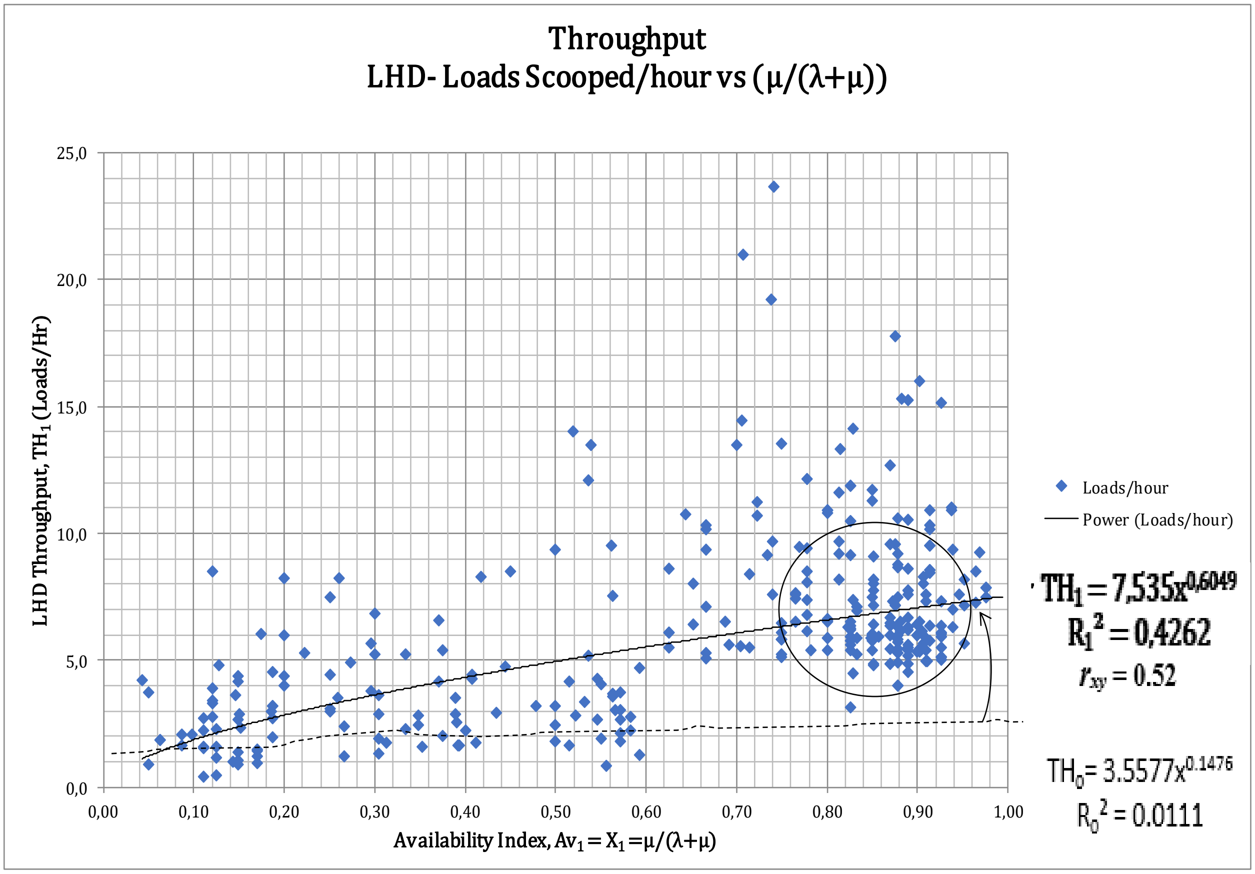


Figure 4.21 – Throughput vs Availability Index at MineABC at improved loads/h

This results shows that the cycle times can be made to have influence on the loaders' station throughputs by greater control on the process and ensuring that the cycle is put under strict controls and continuous monitoring to deal with any possible delays, including real time controls.

4.5.2.3. Improved Plant Reliability(MTBF) – reducing failure rate(λ)

Another very important decision factor in improving productivity of the loaders is through improving availability index of the production station $\mu/(\lambda+\mu)$. The availability index is a function of the plant's reliability represented by the Mean-Time Between failures (MTBF), or the inverse of it which is the failure rate (λ) as well as the Mean-time to Repair (MTTR) or the repair rate (μ).

As discussed in section 4.5.2.2 above, one important tactic to employ for improving the loader's throughput is through reduction in loader cycle times but at the same availability index rate. Another important tactic will be to improve the machine availability index through improving the plant reliability.

Plant reliability is improved through reduction in failure rates λ of the equipment (in other words increasing MTBF). A look at varying the failure rate at fixed cycle time times is also done using the same equation 4.28 but this time varying the constant Kc.

Constant Kc is represented by equation (4.15) and various values of Kc can be given at various values of λ and μ

$$K_c = \left(\frac{\mu}{\mu+2\lambda}\right).\left(\frac{2+ 2\lambda+\mu)}{2+\mu+\lambda}\right) \qquad (4.15)$$

If the MTTR is average 3.45 hrs over the period and it will be assumed to remain constant since it reflects the maintenance logistics in the mine, then $\mu = 0.29$**.** Table 4.5 show the variation of the constant Kc at various failure rates and a constant repair rate of 0.29.

Variation of Constant Kc with failure rate (λ)

$\mu = 0.147$ (MTTR = 6.78 hours)

MTBF (Hrs)	0.75	1.70	2.91	4.52	6.78	10.17	14.29	27.12	61.02	Infinity
λ	1.33	0.59	0.34	0.22	0.15	0.10	0.07	0.04	0.02	0
Kc	2.38	1.64	1.39	1.26	1.18	1.12	1.08	1.05	1.02	1

Table 4.5 – Variation of loader cycle time constant Kc with failure rate λ

Based on equation (4.15), plotting of *TH* vs *CT* for the LHDs at various station failure rates indexes λ can be possible and this gives the Figure 4.22. Figure 4.22 is a decision chart which illustrates the variation of the throughputs versus loader cycle time at various equipment failure rates (λ) values. This is an important decision chart because at a fixed cycle time, it shows how much throughput can be increased by improvement in the MTBF (or reduction in λ).

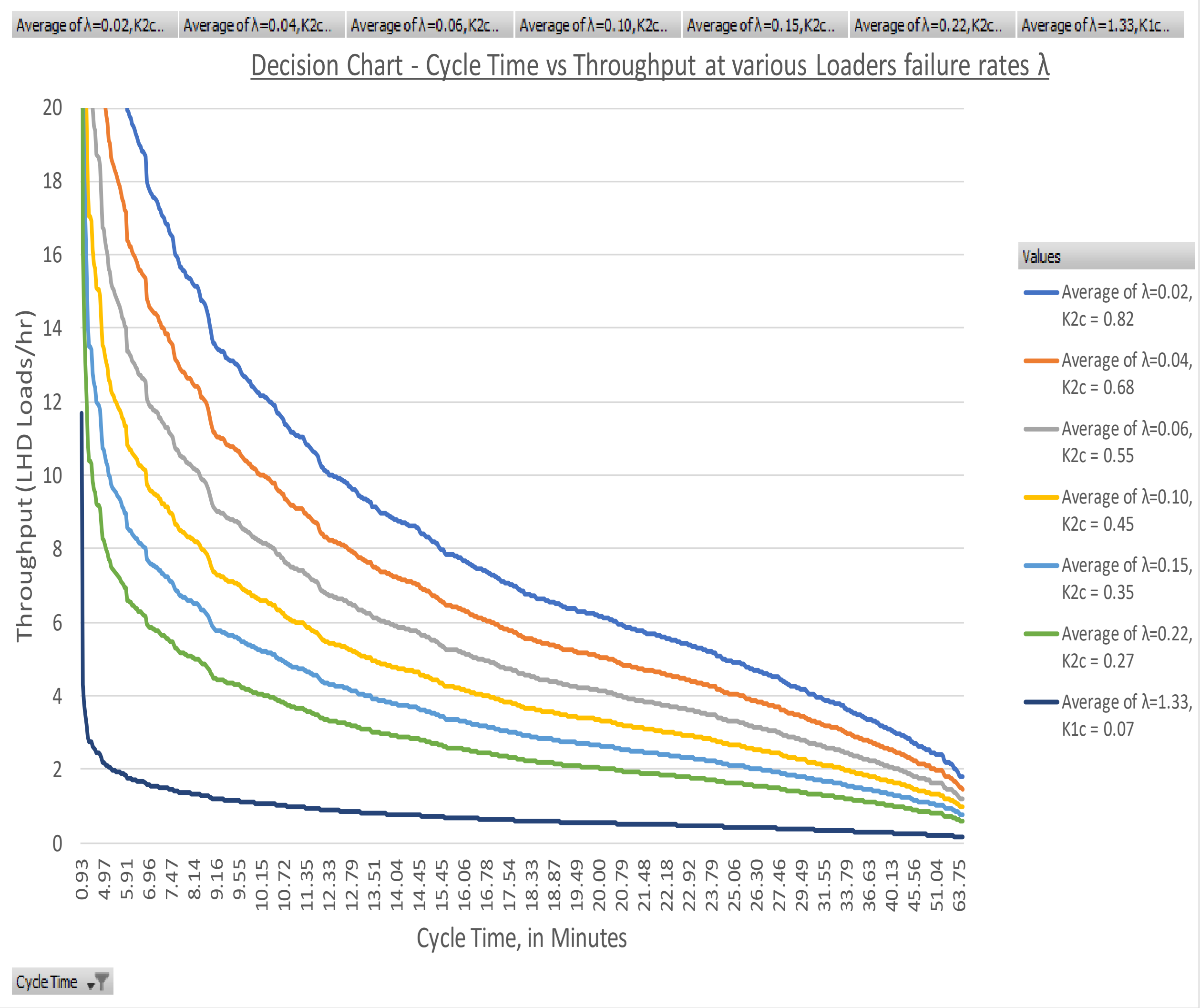


Figure 4.22 – Decision Chart - Throughput vs cycle times at varying failure rates (λ)

Various maintenance tactics can be employed to improve the reliability of the plant. However, one of the scientific ways is to look at the failure patterns of the loaders of the period. This was made possible as enough data to look at the machine performance during this period was available.

Using the failure data available, two charts were plotted for assisting in making reliability decisions on the plant as follows. The first chart is that of Lifetime age vs failure rate of equipment, the second chart is lifetime age vs availability Index based on Table 4.4 data

The first Figure 4.23 shows that if we fit a polynomial curve to the data, the failure rate of the equipment tends to follow a bath-tub curve represented by equation :

$$Y = 9.(10^{-11})\, x^2 - 4.(10^{-6})x + 0.0959 \qquad (4.16)$$

Which is an equation of the form, $Y = Ax^2 - Bx + C$, of which the turning point of the Figure is

$$\frac{dy}{dx} = 2Ax - B = 0,$$

$$2.9.(10^{-11})x - 4.(10^{-6}) = 0,$$

Giving x = 22,222 hrs, and y = 0.051 failures/hour

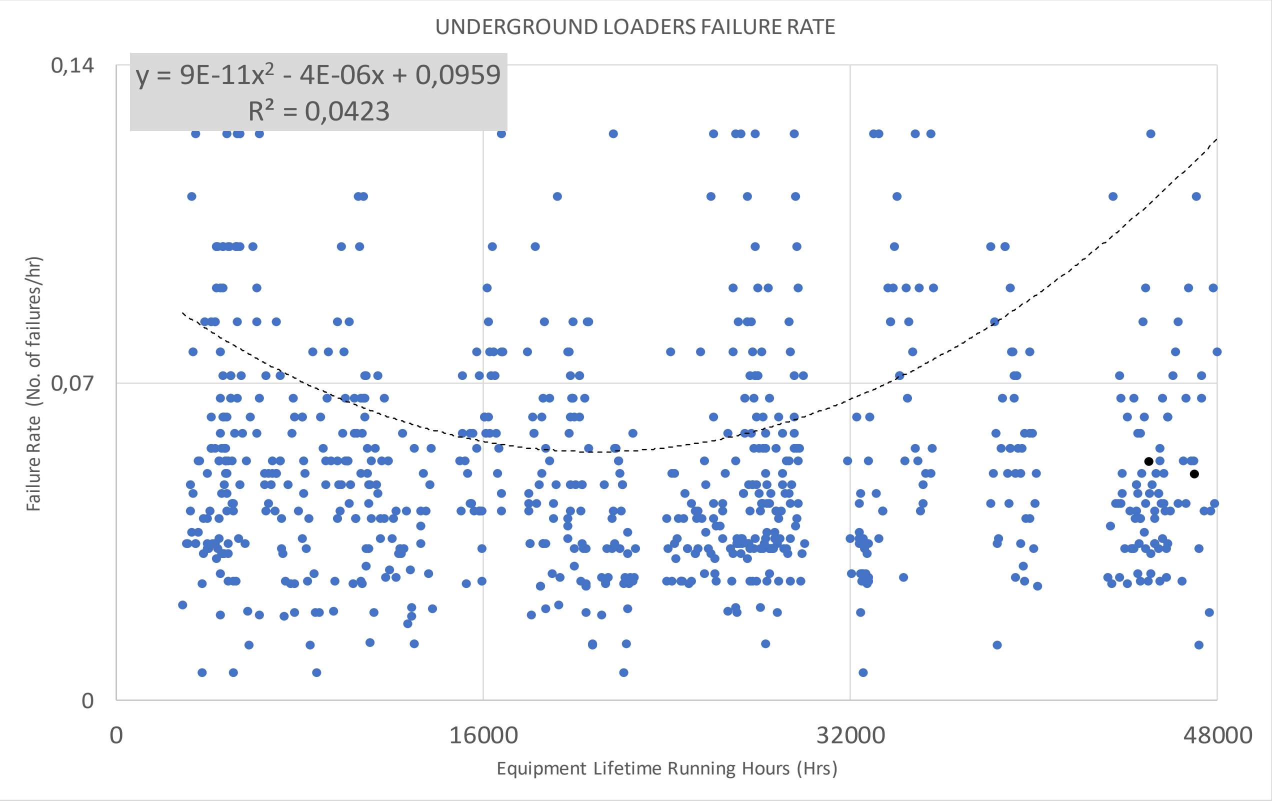


Figure 4.23 – Loaders (LHDs) lifetime age vs failure rate

The Coefficient of Determination, ***R^2 of 0.043*** for Figure 4.23 shows that there is little regression between the two variables. This may mean that the maintenance regime at the mine might not been having any influence to the performance of the equipment. For illustrative purposes, the result of Figure 4.23 may mean that the failure rate of the equipment started to increase at average 22,222 hours, and the minimum failure rate is 0.051 (or an MTBF of 19.43 hours). From the researcher's own experience a failure rate of 0.025 failures/h (or MTBF of 40 hours) is normally considered best practice for underground operations.

This age of 22,222hrs may represents the life of the equipment that required major interventions such as a full rebuild. In the case of MineABC, out of the 21 machines in the fleet, 10 of them (48%) were above the 22,222hrs without any rebuild/asset renewal work having been done.

A plot of the availability index also gave Figure 4.24.

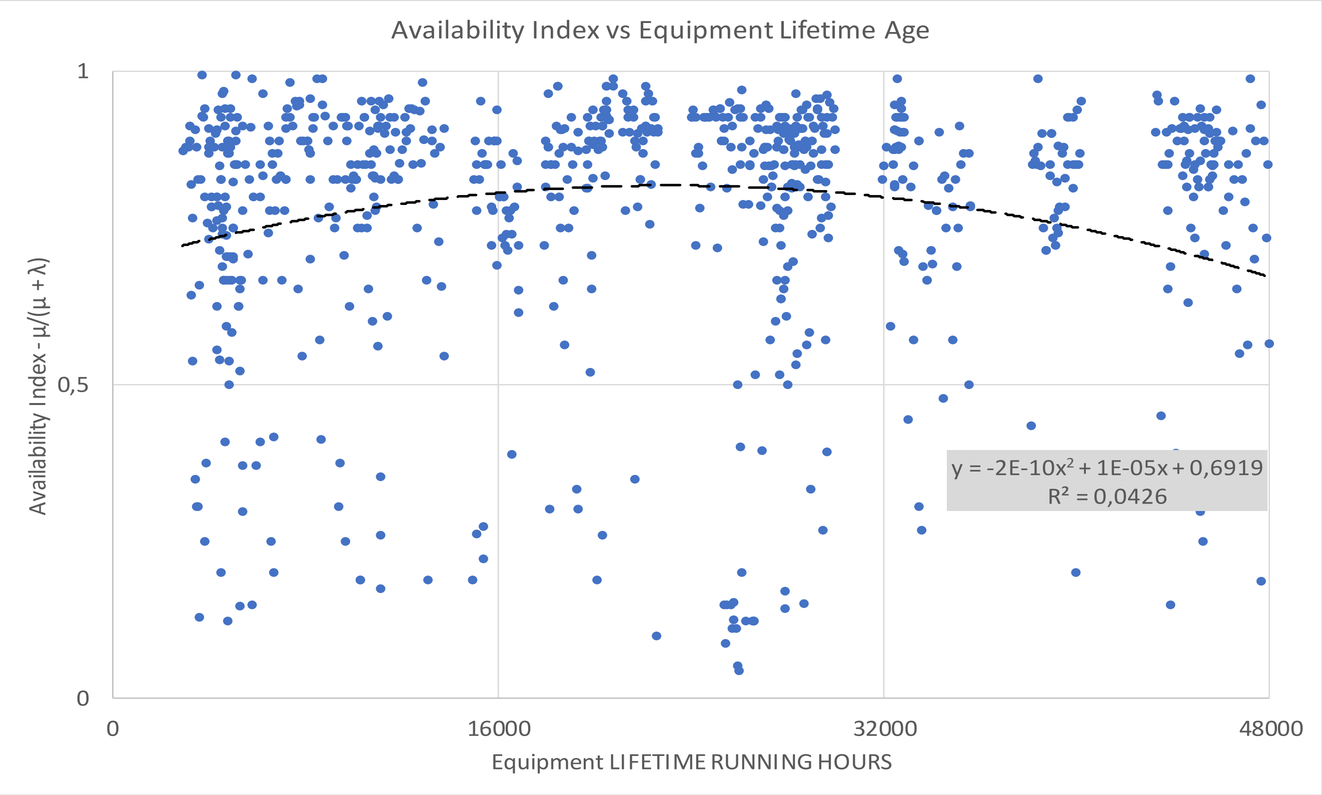
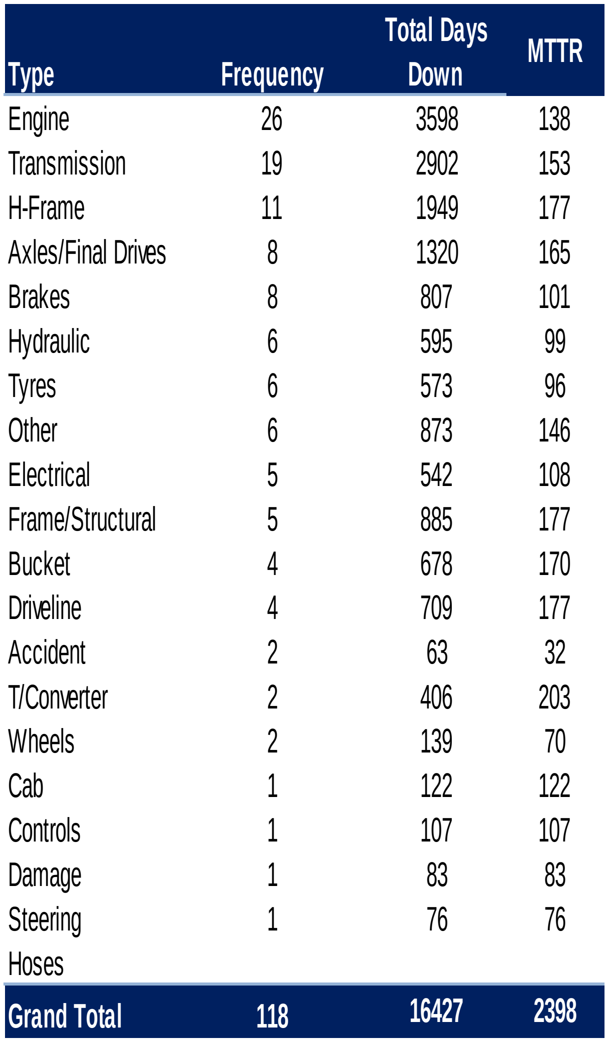


Figure 4.24 – Loaders (LHDs) lifetime age vs availability index

The availability index Figurev4.24 replicated the direct opposite of the failure rate Figure 4.23 which is expected as the availability index is expected to be dropping as the age of the machine is increasing. Also the $R^2=0.0426$ was also very low therefore illustrating that there is little correlation between the two variables of age vs. availability.

However, these two Figures 4.23 and 4.24 may be used to illustrates the opportunities that could be available in improving the reliability through renewing the fleet by rebuilding or by replacement. These are economic decisions which are discussed in Chapter 7. Table 4.6 illustrates some of the areas that would need to be worked on to improve reliability as they had the largest impact on plant MTBFs



Type	Frequency	Total Days Down	MTTR
Engine	26	3598	138
Transmission	19	2902	153
H-Frame	11	1949	177
Axles/Final Drives	8	1320	165
Brakes	8	807	101
Hydraulic	6	595	99
Tyres	6	573	96
Other	6	873	146
Electrical	5	542	108
Frame/Structural	5	885	177
Bucket	4	678	170
Driveline	4	709	177
Accident	2	63	32
T/Converter	2	406	203
Wheels	2	139	70
Cab	1	122	122
Controls	1	107	107
Damage	1	83	83
Steering	1	76	76
Hoses			
Grand Total	**118**	**16427**	**2398**

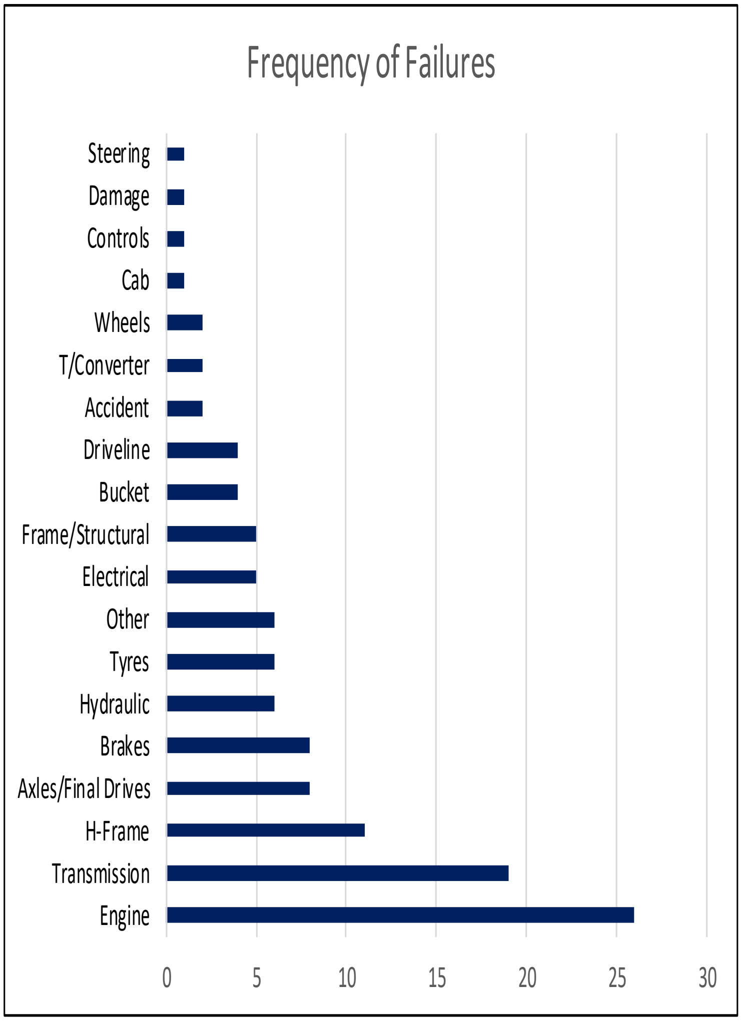


Table 4.6 – Major contributors to failure rate of the loaders

4.5.2.4. Improved Mean-time to Repair (MTTR)

Another important area identified which has great potential of value creation was through reducing the MTTR. Mean time to repair is also an engineering function which involves the logistics around the time to effect repairs on equipment. MTTR includes time to repair as well as time to respond to the breakdown.

One important area which has an impact on mine performance is the response to equipment breakdowns and emergencies. Most mines would run a dispatch office of some sort where equipment breakdowns are reported. However, delays are normally experienced between the time the breakdown occurs, to the time the mechanic/artisan gets on the job to do it.

Figure 4.25 is an analysis of the repair times at MineABC for all the loaders in the year 2015. The table show that 0.5 hours was spent in reporting a breakdown, 0.9hrs was the reaction time which was the time taken from when the breakdown was reported to the artisan until the artisan starts working on the breakdown. Actual repair time was only 46% of the total equipment downtime.

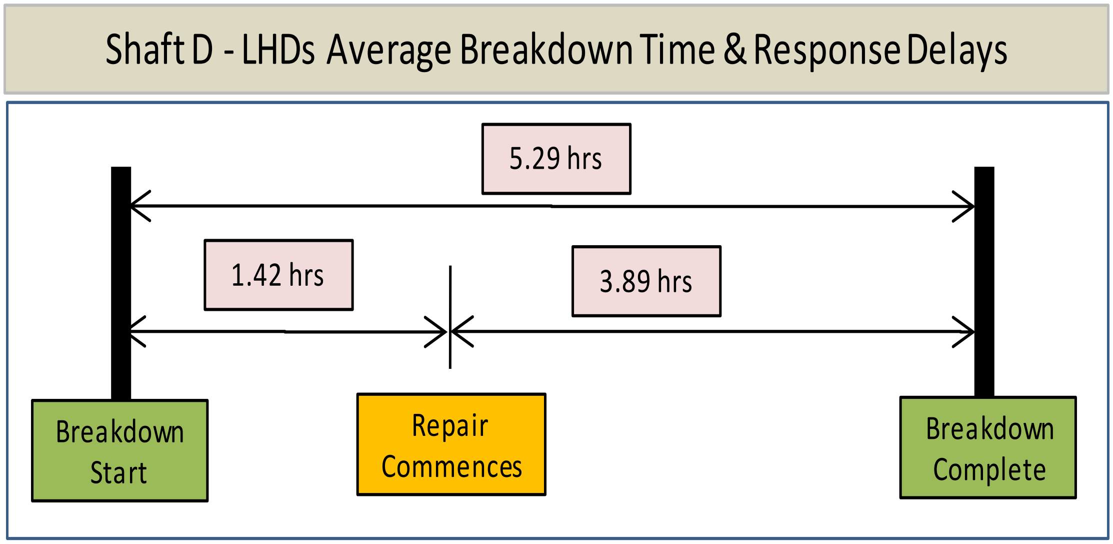


Figure 4.25 – Loaders (LHDs) breakdown response times

Figure 4.26 describes the distribution of time also show opportunities for improvements on the MTTR

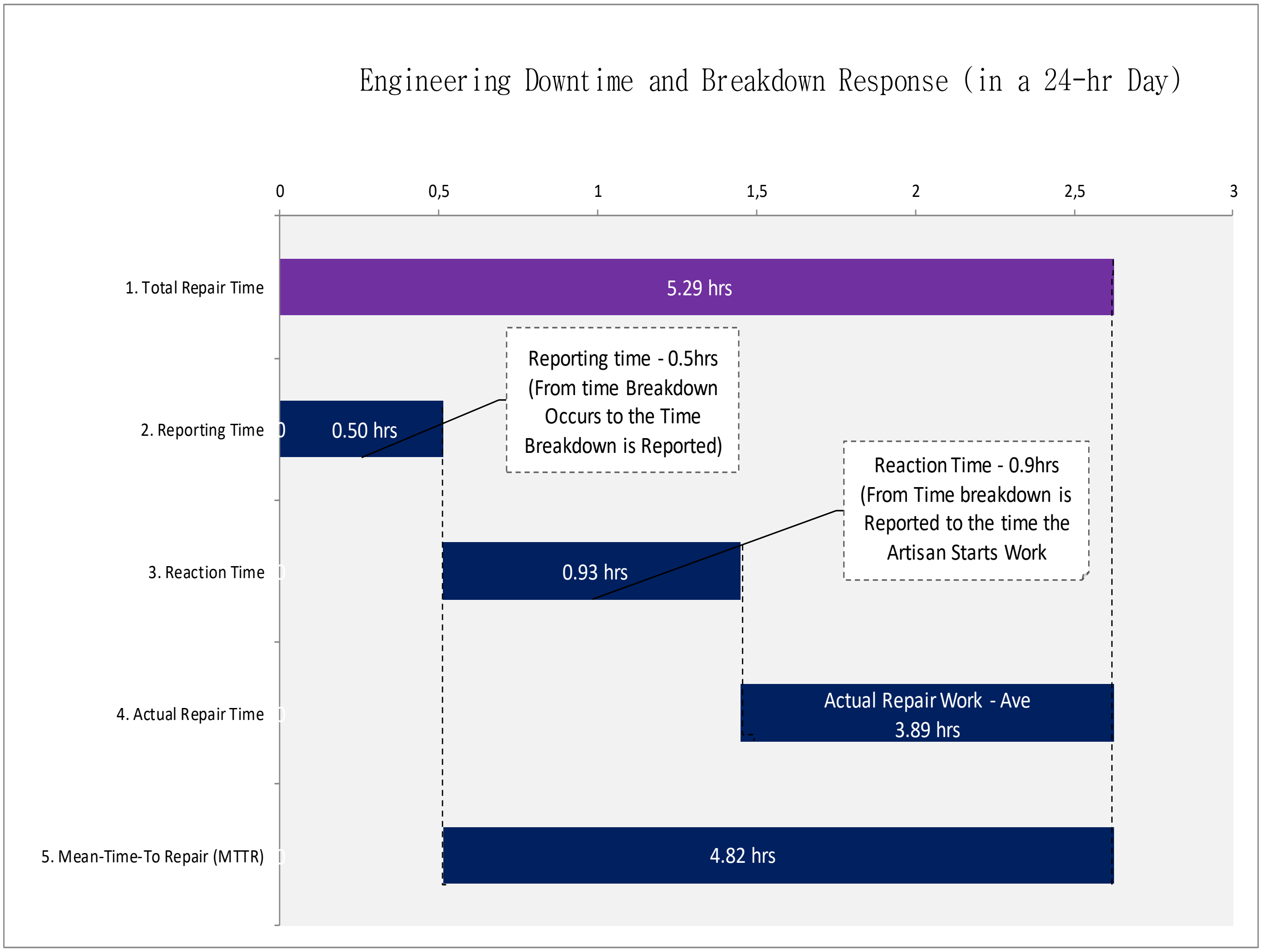


Figure 4.26 – Loaders (LHDs) breakdown response time distributions

The impact of MTTR as an improvement can also be seen by developing a decision chart based on the throughput equation (4.13)and the constant Kμ given by equation (4.15).

$$TH = K\mu.\left(\frac{1}{CT}\right) \tag{4.16}$$

$$K\mu = \left(\frac{\mu}{\mu+2\lambda}\right).\left(\frac{2+2\lambda+\mu)}{2+\mu+\lambda}\right) \tag{4.17}$$

If the failure rate is assumed fixed at the improved value of 0.04 (MTBF 27.12 h), a variation of the constant Kμ is shown to vary with the various values of the MTTR as shown by table 4.7.

Variation of Constant Kμ with Repair rate (MTTR) (λ)

λ = 0.04 (MTBF = 27.12 hours)

MTTR (Hrs)	22.50	20.00	17.50	15.00	12.50	10.00	7.50	5.00	2.50
μ	0.04	0.05	0.06	0.07	0.08	0.10	0.13	0.20	0.40
Kμ	0.36	0.39	0.42	0.46	0.51	0.57	0.64	0.73	0.85

Table 4.7 – Variation of Constant Kμ at various repair rates (μ)

A decision Figure 4.25 of throughput values at different repair rates μ, but fixed λ and cycle times is then plotted. The Figure is useful in simulating the various throughputs at various MTTR values.

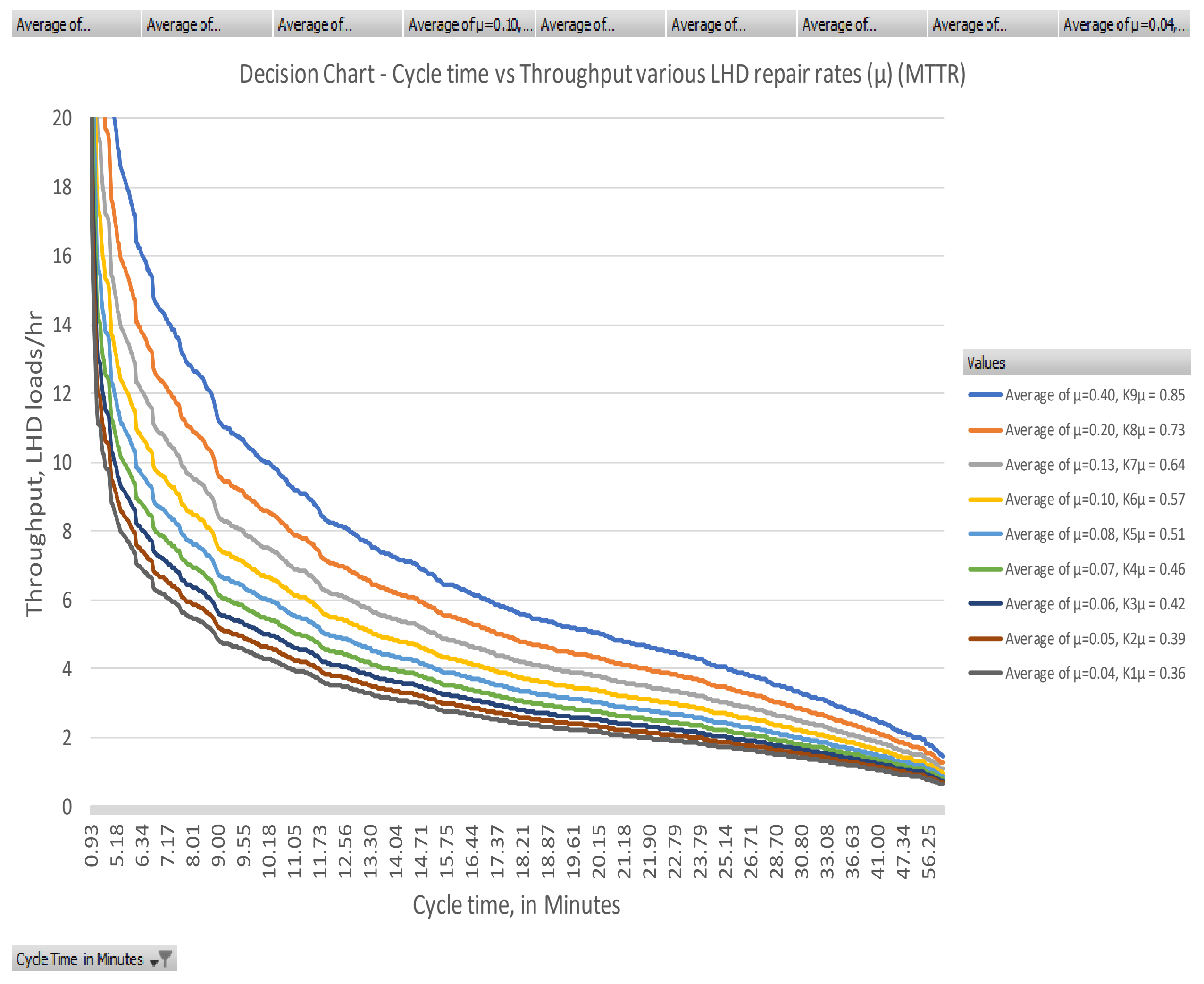


Figure 4.27 – Decision Chart - Throughput vs cycle times at varying repair rates (μ)

4.6. CHAPTER CONCLUSIONS

This chapter focused on carrying out an analysis on the key technical factors which impact production rates and how they can unlock value in a trackless mine situation. This was based on using the historical operating information collected at MineABC which was a large copper and nickel mine with four different operating shafts. Using the mine's historical data and the tools such as theory of constraints (TOC), it could be illustrated that the mine indeed had bottlenecks which needed to be looked at if it was to improve its productivity.

The analysis was divided into three main decision levels. The first level was the system level. At this level the key factors which impact output were found to be the total residence time of the material in transit (in this case the ore) in the system. It was indicated that the rate of output at system level depended on the material in the system and the delay times and value-adding and non-value adding activities were illustrated by a value stream map.

The next level of analysis was at the process level. At this stage the focus was on the impact of gross cycle time of the various work stations. The impact of gross cycle time is seen when compared with the Takt time. The Takt time in this case is the time required to process a ton of ore inorder to meet the daily demand. If the gross cycle time is greater than the Takt time, that process is constrained and will not be able to meet the production targets. In this case the drill and blast, the loading and the hauling workstations were found to be constrained processes.

The third decision level was on the equipment level. At this level the factors which impact through put was shown to be the equipment reliability, maintainability and capacity. The equipment reliability was analysed by the impact of the failure rate (λ), and maintainability analysed by the impact of repair rate (µ) on the output. It was shown that the capacity of the equipment is affected by these equipment cycle times. Three decision Charts - Figure 4.20, Figure 4.22 and Figure 4.27 were developed to assist in making the various decisions on equipment performance using reliability and maintainability data.

5. ACTIVITY ANALYSIS FOR IMPROVED EQUIPMENT UTILIZATION

5.1. CHAPTER OVERVIEW

The purpose of this chapter is to look at overall system factors which impact the total operational hours (OT) of equipment as illustrated before by equation (4.1). Chapter 4 considered the technical factors affecting the station production rate in terms of throughput rate (TH). This chapter considers factors affecting the OT factor. Processes at MineABC were also used as main study.

Total Tonnage = Station throughput x Total Effective Utilized Hours x Fill factor

$$Q_T \textit{ (tons)} \quad = \quad \text{TH (Loads/h) x OT (h) x BF (Tons/load)} \tag{4.1}$$

Total effective operational time is of critical importance in a mining production process to be able to meet the production targets. This chapter focuses on an analysis of critical activities which had an impact on maximizing the effective equipment utilized hours at MineABC.

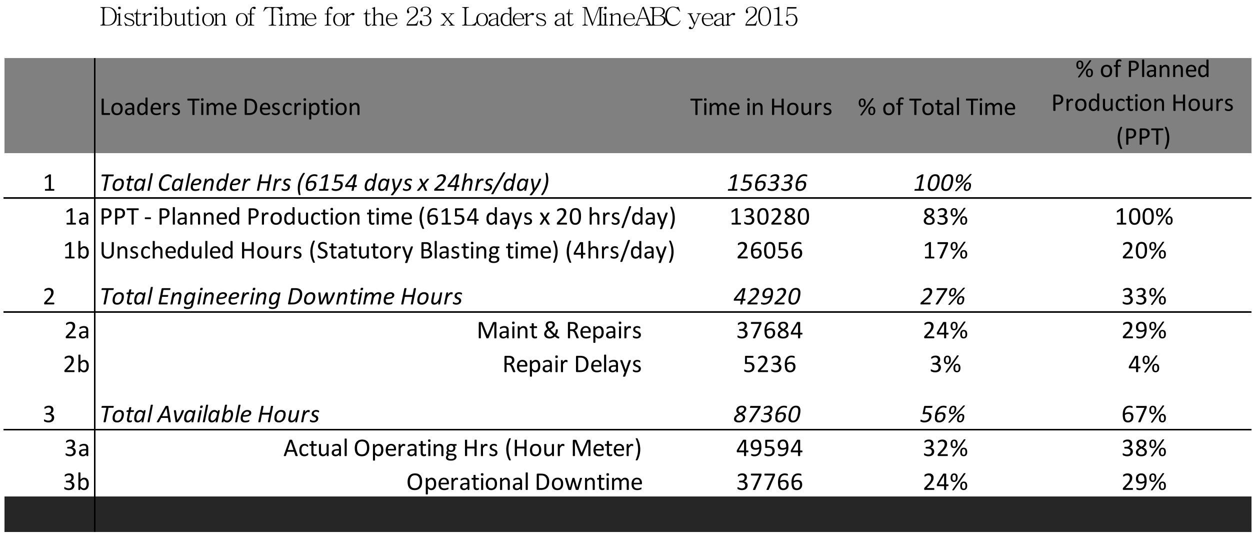
The first part of this chapter considers elements which make up production time and analyzes the activities and delays inherent in a trackless mine. From there, a logical concept for an improved real-time decision support system for underground mining is formulated in practice to show how the system can be developed.

This Chapter comprises:

5.1 Overview of the chapter
5.2 Elements of production time
5.3 Analysis of activities in a trackless production system
5.4 Analysis of delay activities
5.5 Processes for managing and control of trackless operations
5.6 Chapter conclusion

5.2. ELEMENTS OF PRODUCTION TIME.

Chapter 4 showed that the largest cycle time constraints at MineABC were due to the loading process. This gave interest to make a further detailed analysis of the time distribution of the loading process. A time distribution analysis for the 23 underground loaders (LHDs) at MineABC is illustrated by Table 5.1 for the full year 2015.



Distribution of Time for the 23 x Loaders at MineABC year 2015

	Loaders Time Description	Time in Hours	% of Total Time	% of Planned Production Hours (PPT)
1	*Total Calender Hrs (6154 days x 24hrs/day)*	*156336*	*100%*	
1a	PPT - Planned Production time (6154 days x 20 hrs/day)	130280	83%	100%
1b	Unscheduled Hours (Statutory Blasting time) (4hrs/day)	26056	17%	20%
2	*Total Engineering Downtime Hours*	*42920*	*27%*	33%
2a	Maint & Repairs	37684	24%	29%
2b	Repair Delays	5236	3%	4%
3	*Total Available Hours*	*87360*	*56%*	67%
3a	Actual Operating Hrs (Hour Meter)	49594	32%	38%
3b	Operational Downtime	37766	24%	29%

Table 5.1 – Time distribution for underground loaders at MineABC year 2015

A total of 6,514 combined days was analysed, giving a total of 156,336 hours and an average of 283 days for each loader. The table 5.1 clearly illustrates that the actual value adding time was only 32% of the total calendar hours or 38% of the available production time. 4 hours per day were reserved for the statutory blasting time where no person could enter the mine.

32% Utilized hours is a low value which has high potential to be improved through various methods. Engineering downtime accounted for 27% of calendar time or 33% of planned production time(PPT). Basing on the planned production time (PPT), it means the overall loaders availability was 67%.

A time chart is presented in Figure 5.1 giving clarity on how the time was distributed and which activities were value adding and which were not. In this chapter a method using a system engineering functional analysis approach is used to diagnose activities which had high potential for improvements.

To analyse the time charts, the best place to start is through better understanding of the activities which make up an underground trackless mine production system. After understanding the dynamics around each of the critical activities it is then possible to recommend the areas of improvements.

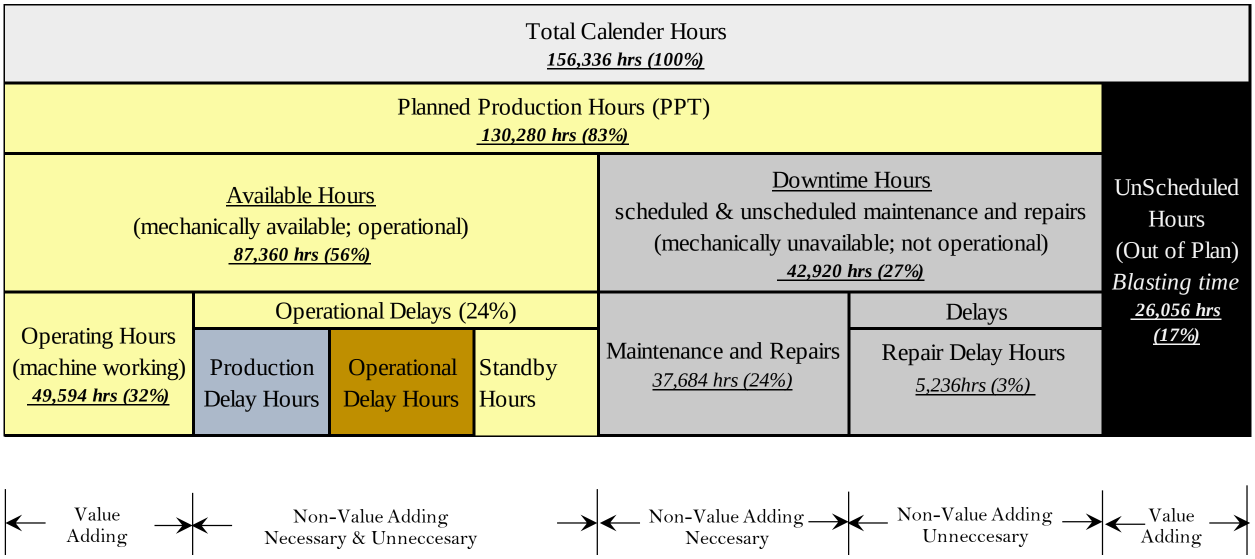


Figure 5.1 – Time distribution for underground loaders at MineABC year 2015

To understand critical activities in the mine, it was best to get a view from key stakeholders regarding day to day activities which needed improvement in decision making. This was done in April 2014 to solicit view from key stakeholders in a brainstorming discussion organized.

After understanding the critical activities in the mine, a detailed activity analysis for the whole underground production system was carried out and used in developing specification lists to assist a in developing of a decision support system. The notion behind this approach was that a proper decision support system could best be configured after understanding the trackless mining process and its dynamic behavior.

5.3. TRACKLESS MINING ACTIVITIES ANALYSIS

5.3.1. Identifying critical activities in a trackless operation

To understand the functions in an underground mine, a qualitative brainstorming session was conducted at ShaftA4 to elicit the user’s views on benefit of implementing a decision support system at the mine. This session involved key supervisors such as mine captains, shift-bosses and shaft engineer. At the time of the survey in April 2014, *MineABC* employed a manual system for monitoring operational activities underground.

Challenges were always present in daily and shift decision making from the manually driven system. A system implemented previously for tagging and monitoring equipment and personnel underground was now dysfunctional due to maintenance and support related issues. A total of 52 activities were identified as typical in the underground trackless mine with a vertical shaft system. The supervisors were asked to do a group qualitative assessment of each key activity in the current operational decision system practice and rank the impact of that activity to production and how efficient the current monitoring and control system was.

The scoring criteria was for importance to production (IMP), score 1 was for low impact or importance to production, score 3 for medium impact and score 5 for high impact. For efficiency (EFF) of the current system, score was between 1 and 10 on sliding scale, with 10 being the current most efficient system and 1 the least efficient current system. A priority ranking of each activity was then done based on the final score which comes from formula 5.1which needed to be addressed was then calculated.

If A = Importance, B=Efficiency of current system, Priority ranking P was calculated as follows.

$$\text{Priority ranking, } P = A \times (11-B) \tag{5.1}$$

The result of the formula is that an activity with a high score means that it must be put on high priority for an improved decision support system. Activity with priority score between 1 to 15 are classified as low priority because the impact and efficiency was acceptable. Score between 16 to 30 was classified as medium and score between 31 to 50 is high. Those on high and medium priority required attention as the current systems were found to be inadequate.

The activities were classified in 7 major categories of importance to operations decision making, namely: monitoring of ore availability, equipment health status monitoring, personnel dispatch and machine allocation, equipment dispatch and consumables, re-entry to check safety status of sections and mining services (water, power, air, ventilation, etc.,), shift production status and monitoring, blasting and re-entry (including secondary blasting).

These activities were further grouped into 5-broad segments, being start of shift (SOS) activities which include status of mining areas, engineering activities and operator Dispatch Activities (Disp), In-shift Activities (In-SHIFT) and End of Shift (EOS) activities.

5.3.1.1. SOS Activities – engineering and resource planning.

Knowing where to mine and control of the crews at the start of the shift were identified as one of the fundamental success factors in a mechanized system. The knowledge of where the draw-points are, who is available to work for the day, time taken by employees to go to work area, etc., were identified as key value adding decisions which defines effective face time. Table 5.2 is heat map which highlights the high priority areas in darker shade and low priority in lighter shade based on the scores for all the identified engineering and SOS activities. 5 activities were classified as on high priority, 12 on medium priority and one was on low priority, with total of 20 activities

5.3.1.2. Equipment and Personnel Dispatch Activities

The next most fundamental control area was on the monitoring and control of equipment and personnel dispatch activities. Appendix C1 illustrates all the heat map with all critical activities identified for equipment and personnel dispatching. These activities were found to have high number of activities requiring high priority, hence a processes that needed more attention. 10 activities were on high priority, 7 on medium priority and 1 on low priority. Thus this part of the shift cycle required a lot of attention as clearly 56% of the activities needing high priority attention.

5.3.1.3. In-shift Activities and End of Shift Activities

In-shift activities are those that take place during the shift. In terms of equipment operations, these are those decisions that operators make on equipment based on instructions from supervisors as well through monitoring of the equipment health status. A lot of functions dynamically occur at this phase of the mining process and large results could be experienced if there is poor control which can be avoided. End of shift activities includes blasting, and what the operators do when shift ends such as refueling for the next shift. Appendix C2 illustrates these activities. 4 activities were on high priority, 6 on medium and 4 on low priority. This activity analysis shows that this part of the process required less attention than the dispatch activities.

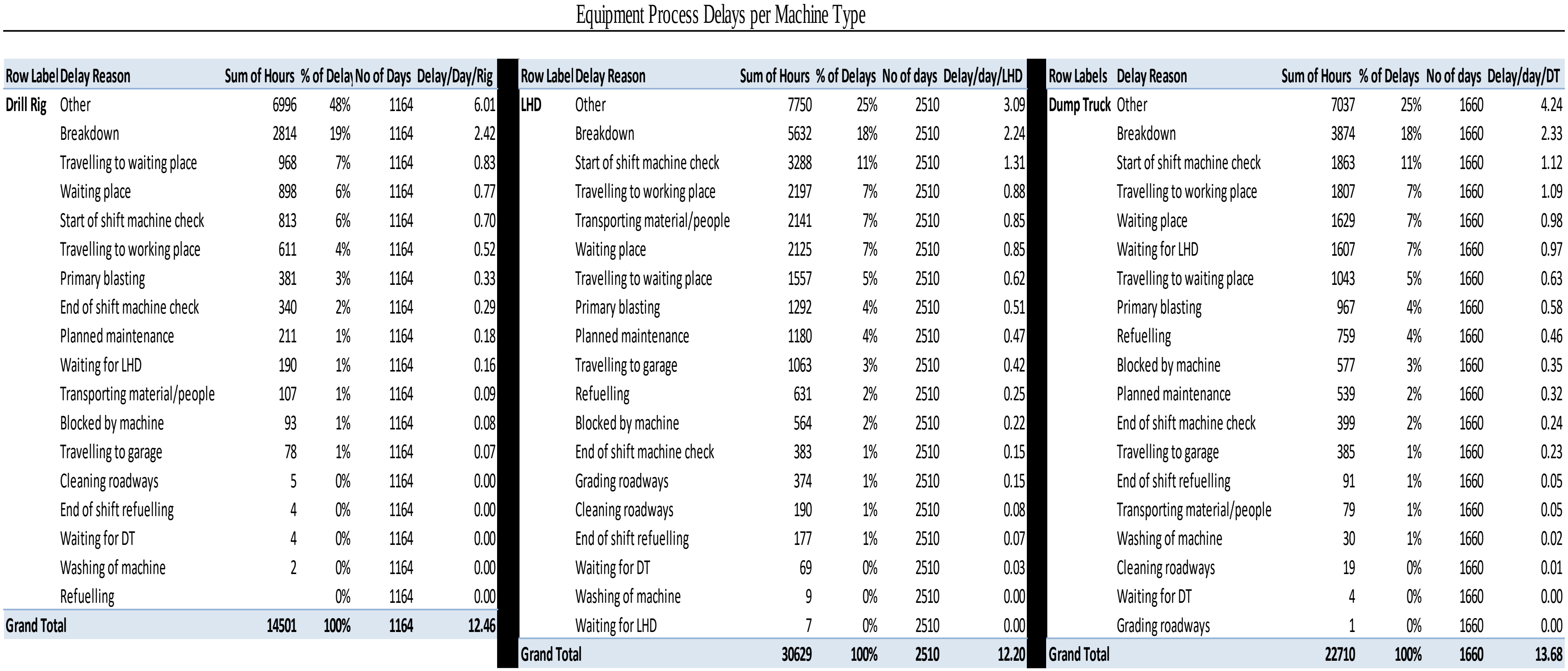
Shift activity analysis - HEAT MAP FOR DAILY ENGINEERING & START OF SHIFT ACTIVITIES

				RATINGS			
Ref	**ACTIVITY**	**Responsibility**	**Current Scenario**	**IMP**	**EFF**	**Priority**	**Stakeholder required future**
SP1	**AVAIL DAILY MINING PLAN - MINING OPERATIONS**						
SP1-1	Provide Monthly Plan	Tech-Services	Monthly plan provided start of month	5	7	20	Access on-line and update continously
SP1-2	Face Layouts	Tech-Services	Manual plans	5	5	30	Provide electronic geological maps
SP1-3	Mining Positional Data	Tech-Services	Need to monitor if mining according to plan, only know after survey	5	6	25	Electronic geological maps and updated continously
SP1-4	No of Ends Available to mine	Mine Supt.	Manual Handover EOS	5	9	10	Updated electronically
SP1-5	Quantity of Production in sections	Mine Supt.	Estimates/Unknown	5	9	10	"
SP1-6	Daily Mining Plan	Mine Supt.	Deciding where to mine start of shift a major challenge	5	3	40	"
SP2	**EQUIPMENT HEALTH & STATUS**						
SP2-1	Machine Status End of Shift (EOS)	Shift boss	All machines are parked in w/shop after shift except when there is a breakdown	5	3	40	Equipment tagging, identify location of each machine real-time
SP2-2	Machine Status Start of Shift (SOS)	Foreman	Relies on report from operators	5	5	30	Machine health status monitored by telemetry and displayed on supervisors computer
SP2-3	Machine Location	Supervisors	Machine location can be a challenge if machine breaks down in sections	5	7	20	Equipment tagging, identify location of each machine real-time
SP2-4	Daily Pre-shift Lube checks	Mechanic		5	4	35	
SP2-5	Daily Pre-shift Checks	Operator	Operator logging & behaviour monitoring	5	6	25	
SP2-6	Fuel and Lubricants status	Maint. Planning	Sometimes we run out of Fuel/Lubricants	3	7	12	Monitor electronically
SP2-7	Re-fuelling	Operator	Time taken for refuelling is not monitored	5	5	30	
SP2-8	Release machine to production	Mechanic	Machines parked haphazardly, blocked machines	5	3	40	Update dispatch status in real-time
SP2-9	PM - Maintenance Schedule	Maint. Planning	Schedule available but changes agreed between foreman & shiftboss	5	8	15	Alarms for non-compliance to schedules
SP2-10	MDE - Execute PM tasks	Foreman	PMs done on fixed time basis instead of hour/usage based	5	2	45	Monitor PMs electronically based on hour meters
SP2-11	Fixed Plant - Shutdown Execution	Foreman	Shutdown overuns	5	6	25	
SP2-12	Downtime occurance reporting	Operator & Mechanic	Breakdown is reported to clerk on surface who in turn phones w/shop. Operator must get nearest place with phone to update breakdown to clerk.	5	6	25	On-line equipment status reporting real-time
SP2-13	Breakdown Response	Mechanic	1.41hrs Delay per breakdown. Mechanic must get transport, assess breakdown, come back collect tools and resources and then go to fix machine.	5	6	25	Alarms on breakdown status continously
SP2-14	Machine availability	Maint. Planning	Conflcting information - limping machine	5	5	30	Electronic update of downtimes

Table 5.2 – Start of Shift (SOS) activities

5.4. ANALYSIS OF ACTIVITY DELAYS

Figure 5.1 showed the low effective utilization hours of loaders for MineABC due to operational and engineering related delays. A further analysis of delays was done to identify the activities which constitute the delays, and the distribution of these process delays is illustrated in table 5.3. Deduction from table 5.3 is that mining at MineABC had a lot of interruptions to process flow due to equipment and system delays such as breakdowns and late arrival of employees.



Equipment Process Delays per Machine Type

Row Label	Delay Reason	Sum of Hours	% of Dela	No of Days	Delay/Day/Rig
Drill Rig	Other	6996	48%	1164	6.01
	Breakdown	2814	19%	1164	2.42
	Travelling to waiting place	968	7%	1164	0.83
	Waiting place	898	6%	1164	0.77
	Start of shift machine check	813	6%	1164	0.70
	Travelling to working place	611	4%	1164	0.52
	Primary blasting	381	3%	1164	0.33
	End of shift machine check	340	2%	1164	0.29
	Planned maintenance	211	1%	1164	0.18
	Waiting for LHD	190	1%	1164	0.16
	Transporting material/people	107	1%	1164	0.09
	Blocked by machine	93	1%	1164	0.08
	Travelling to garage	78	1%	1164	0.07
	Cleaning roadways	5	0%	1164	0.00
	End of shift refuelling	4	0%	1164	0.00
	Waiting for DT	4	0%	1164	0.00
	Washing of machine	2	0%	1164	0.00
	Refuelling		0%	1164	0.00
Grand Total		**14501**	**100%**	**1164**	**12.46**

Row Label	Delay Reason	Sum of Hours	% of Delays	No of days	Delay/day/LHD
LHD	Other	7750	25%	2510	3.09
	Breakdown	5632	18%	2510	2.24
	Start of shift machine check	3288	11%	2510	1.31
	Travelling to working place	2197	7%	2510	0.88
	Transporting material/people	2141	7%	2510	0.85
	Waiting place	2125	7%	2510	0.85
	Travelling to waiting place	1557	5%	2510	0.62
	Primary blasting	1292	4%	2510	0.51
	Planned maintenance	1180	4%	2510	0.47
	Travelling to garage	1063	3%	2510	0.42
	Refuelling	631	2%	2510	0.25
	Blocked by machine	564	2%	2510	0.22
	End of shift machine check	383	1%	2510	0.15
	Grading roadways	374	1%	2510	0.15
	Cleaning roadways	190	1%	2510	0.08
	End of shift refuelling	177	1%	2510	0.07
	Waiting for DT	69	0%	2510	0.03
	Washing of machine	9	0%	2510	0.00
	Waiting for LHD	7	0%	2510	0.00
Grand Total		**30629**	**100%**	**2510**	**12.20**

Row Labels	Delay Reason	Sum of Hours	% of Delays	No of days	Delay/day/DT
Dump Truck	Other	7037	25%	1660	4.24
	Breakdown	3874	18%	1660	2.33
	Start of shift machine check	1863	11%	1660	1.12
	Travelling to working place	1807	7%	1660	1.09
	Waiting place	1629	7%	1660	0.98
	Waiting for LHD	1607	7%	1660	0.97
	Travelling to waiting place	1043	5%	1660	0.63
	Primary blasting	967	4%	1660	0.58
	Refuelling	759	4%	1660	0.46
	Blocked by machine	577	3%	1660	0.35
	Planned maintenance	539	2%	1660	0.32
	End of shift machine check	399	2%	1660	0.24
	Travelling to garage	385	1%	1660	0.23
	End of shift refuelling	91	1%	1660	0.05
	Transporting material/people	79	1%	1660	0.05
	Washing of machine	30	1%	1660	0.02
	Cleaning roadways	19	0%	1660	0.01
	Waiting for DT	4	0%	1660	0.00
	Grading roadways	1	0%	1660	0.00
Grand Total		**22710**	**100%**	**1660**	**13.68**

Table 5.3 – MineABC – Equipment delay time reasons

Figure 5.2 is a waterfall presentation of the delay types in the different categories and the impact on the total productive time. The non-legitimate delays such as Operational Delays and Engineering delays offer large opportunities for value creation.

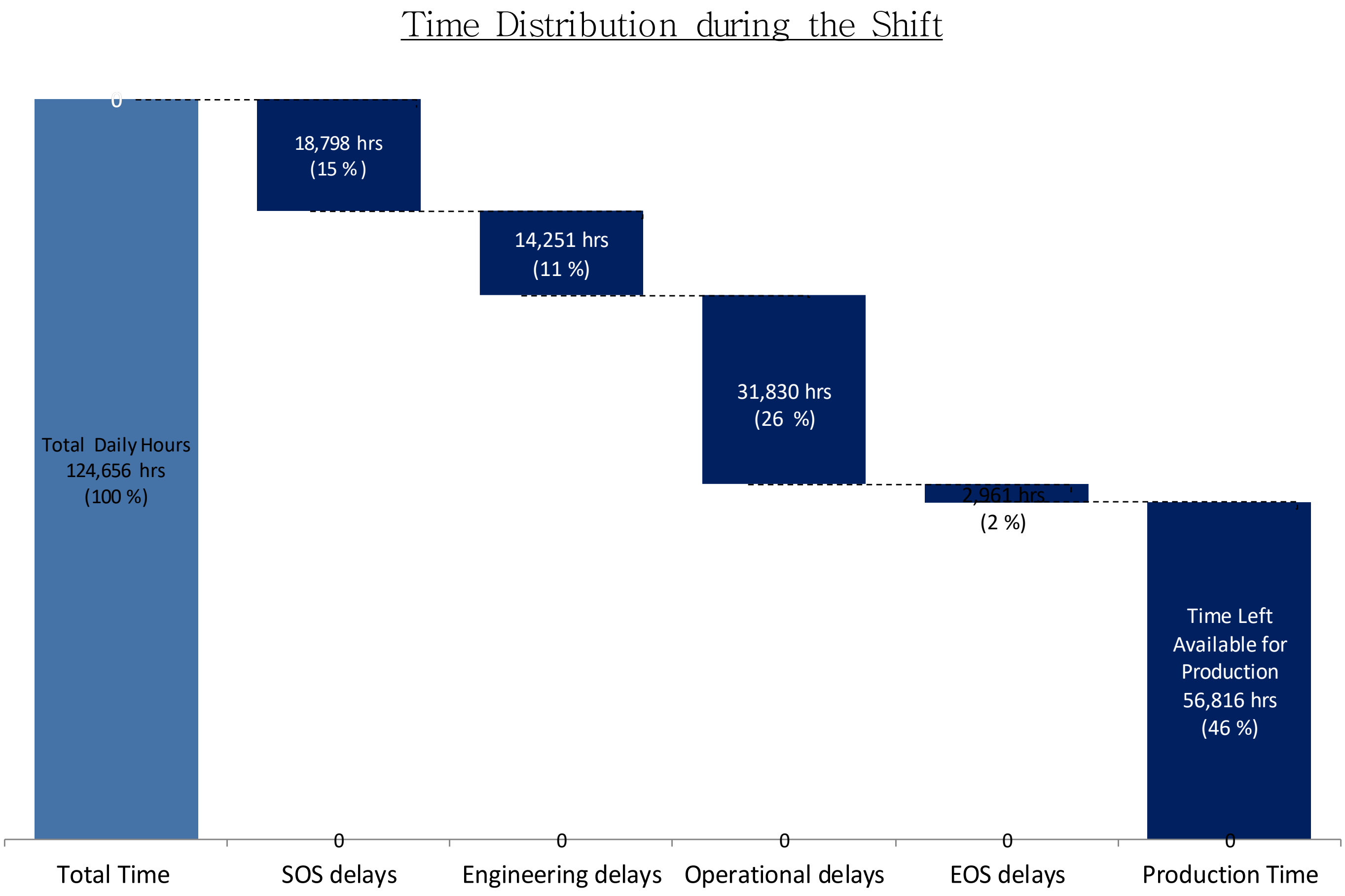


Figure 5.2 – Typical shift time distribution for loaders

Figure 5.3 illustrates typical SOS processes for both day and night shift. As per the mine plan, SOS activities were planned to take 45minutes in total. However, in practice, the SOS activities were taking 2 hours 15 minutes during the day shift and 1 hour 40 minutes during the night shift. This is almost three times the budgeted time.

Largest delays on SOS were during collection of lamps at the lamp room which took average one hour, 30 minutes travelling to waiting place and about 45 minutes at the waiting place. These delays presented opportunities of improvement.

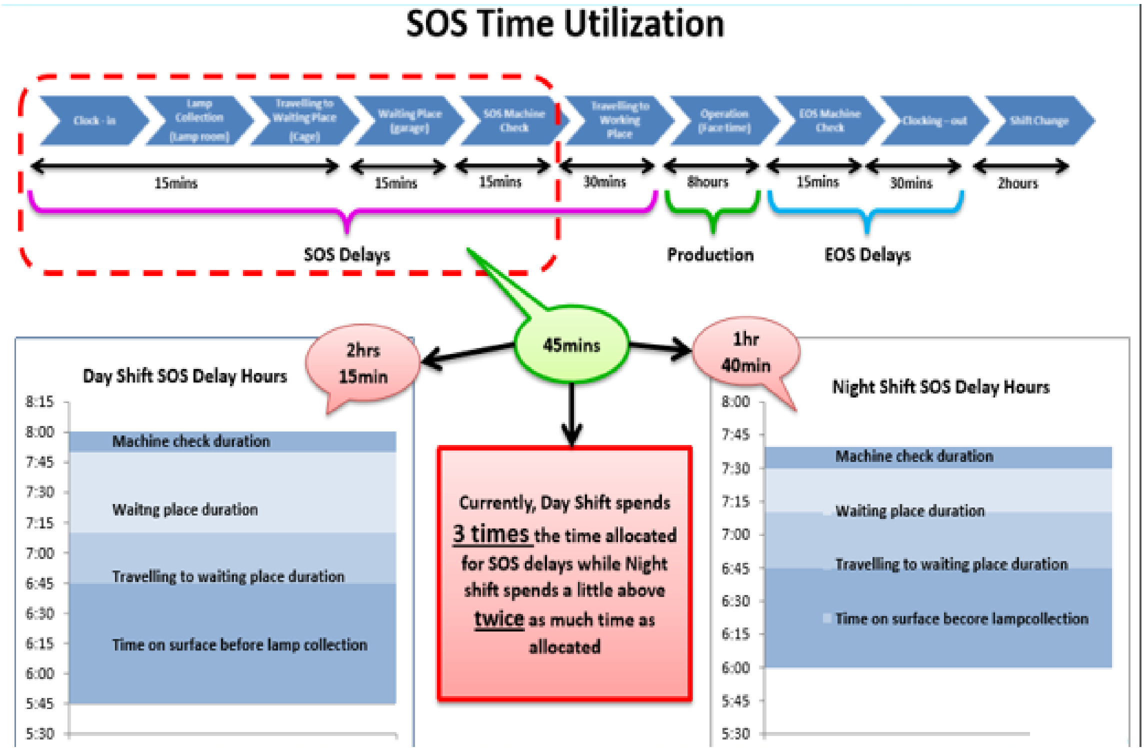


Figure 5.3 – SOS time distributions and delays

Another major source of delay was also with the miner in charge who is a key resource at the face to enable production to commence. An analysis shown in Figure 5.4 showed that 79% of the Miners-In Charge (MIC) arrived at working faces well after the official starting times. In line with this was the late arrival of buses and the delay in employees start of shift times.

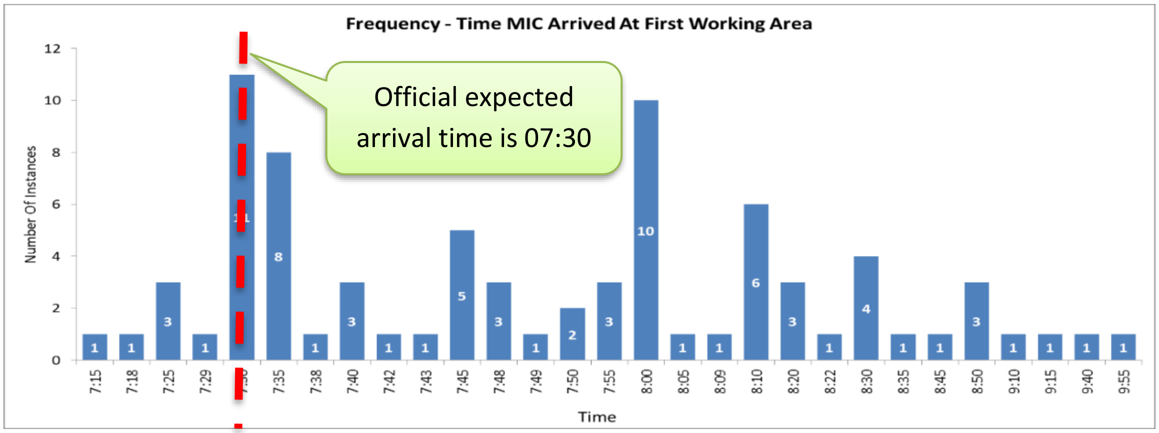


Figure 5.4 – Miner-in-Charge shift starting times

Furthermore, during start of shifts, another major source of delays identified was due to equipment dispatch. An analysis of the dispatch of equipment considered release at ShaftA2 and Shaft A4. Figure 5.5 is a record of the time dumptrucks left the workshop every start of shift and the average number in production every hour over a period of four-months.

The analysis consisted a fleet of 7 trucks expected to meet production targets. Only at 10:00hrs will 85% of the trucks have been released to production as illustrated by the cumulative number of trucks capacity start of shift in Figure 5.5. This was a serious cause for concern. Early in the start of the shift, there were various delays which made it not possible to have all the machines released exactly at start of shift. These delays were not visible to the supervisors and hence there very little control over the process.

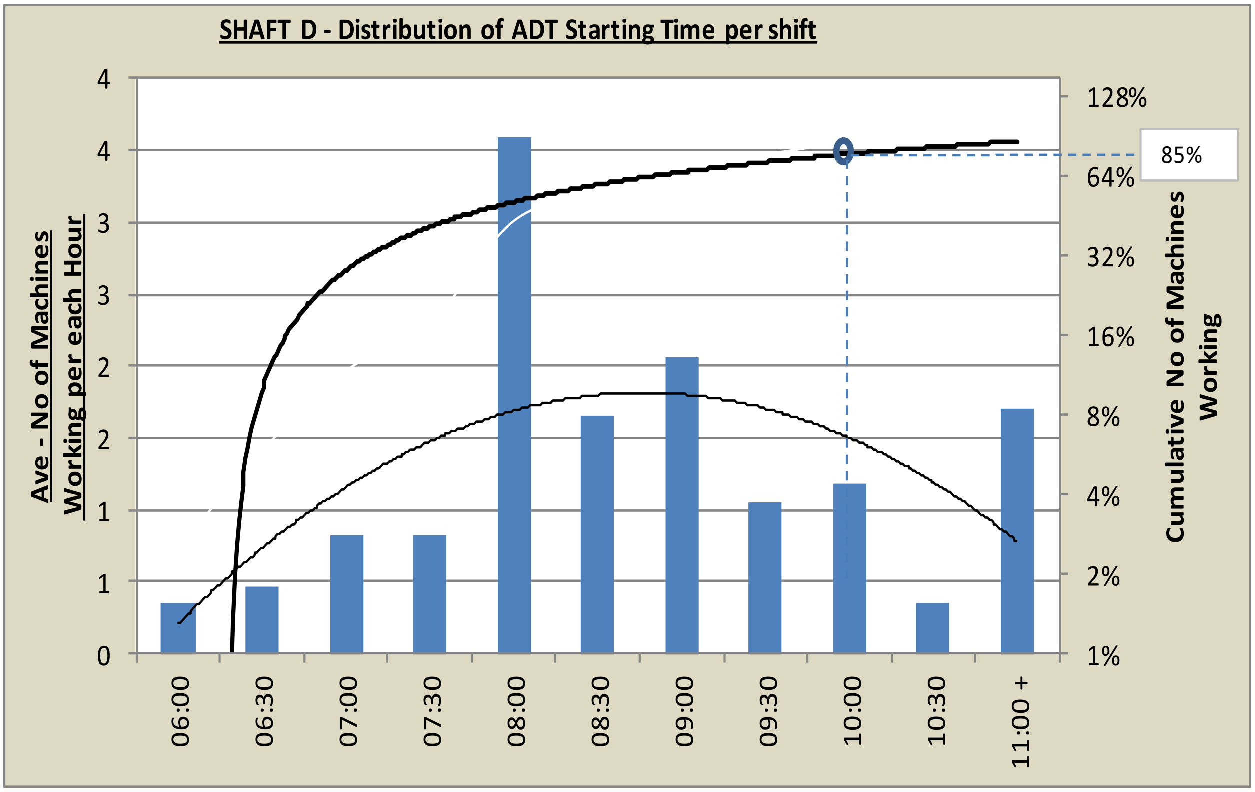


Figure 5.5 – Dumptrucks dispatch times at Shaft A4

The same scenario at ShaftA2 was also analyzed as shown by Figure 5.6 with first machine only released after 2 hours start of shift and last machine 3.5 hours after the shift.

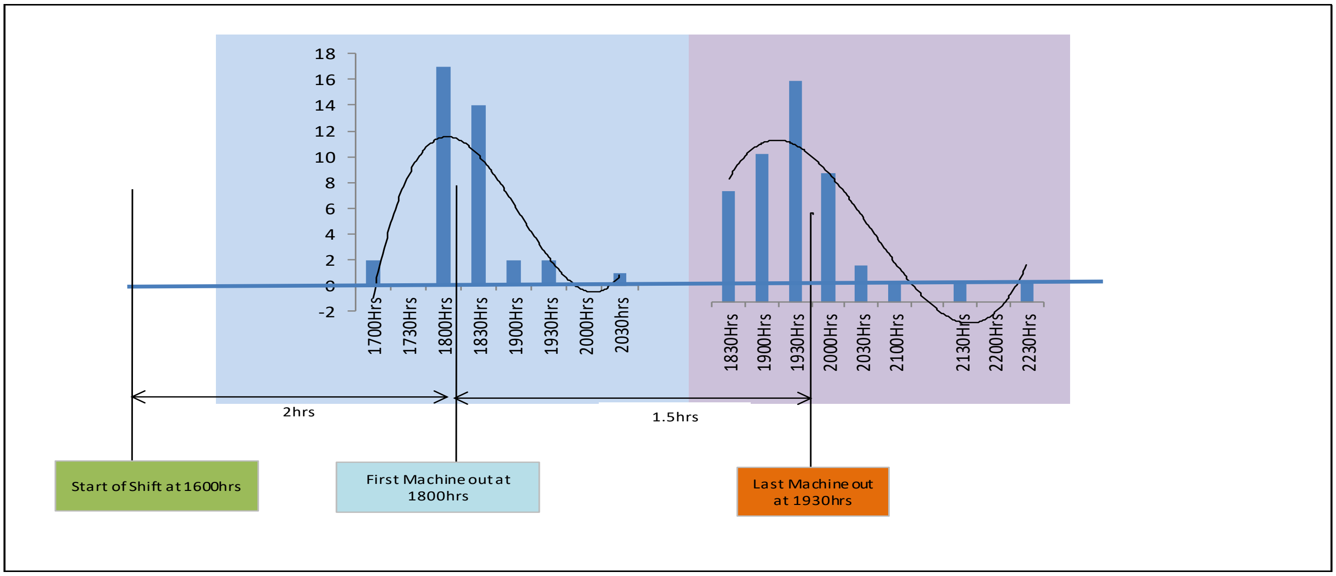
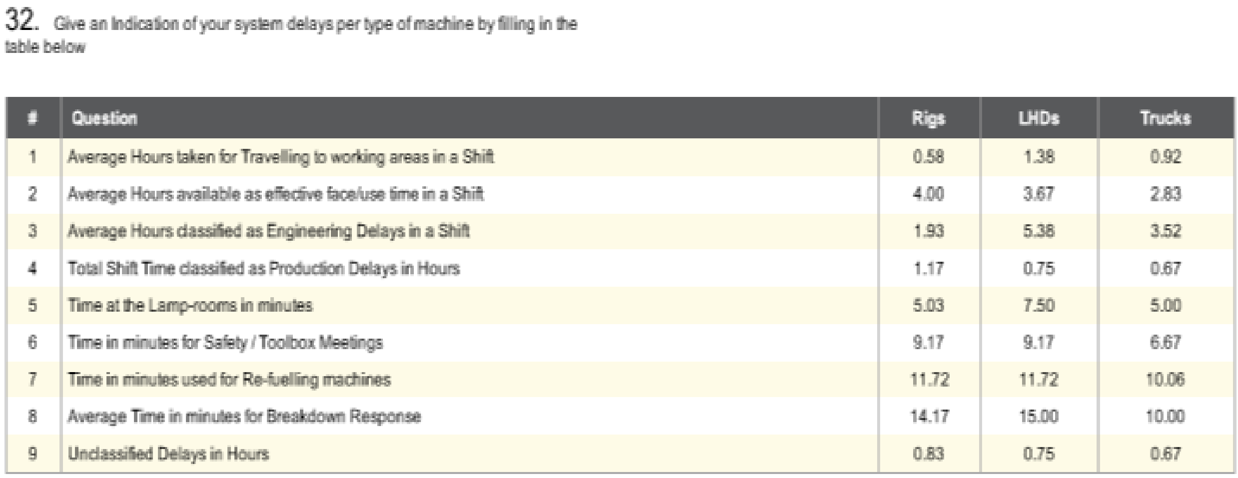


Figure 5.6 – Equipment dispatch time distributions at Shaft A2

For benchmarking purposes, an online survey was also done to try to verify or validate some of the findings from MineABC. Table 5.4 show the results of the survey from the response of seven different mines which responded to the survey. The survey questions details are in Appendix E

A major note from the result in table 5.4 is that typically most of the mines had only an average of maximum 4 hours of face time in a typical 10-hour shift, most of the time was lost in various delays. Engineering related delays were also cited as major delays as high as 5.38 hours in a shift. The results resonated well with those from MineABC.



32. Give an Indication of your system delays per type of machine by filling in the table below

#	Question	Rigs	LHDs	Trucks
1	Average Hours taken for Travelling to working areas in a Shift	0.58	1.38	0.92
2	Average Hours available as effective face/use time in a Shift	4.00	3.67	2.83
3	Average Hours classified as Engineering Delays in a Shift	1.93	5.38	3.52
4	Total Shift Time classified as Production Delays in Hours	1.17	0.75	0.67
5	Time at the Lamp-rooms in minutes	5.03	7.50	5.00
6	Time in minutes for Safety / Toolbox Meetings	9.17	9.17	6.67
7	Time in minutes used for Re-fuelling machines	11.72	11.72	10.06
8	Average Time in minutes for Breakdown Response	14.17	15.00	10.00
9	Unclassified Delays in Hours	0.83	0.75	0.67

Table 5.4 – Benchmark shift delay time analysis for different mines

5.5. DEVELOPING REAL-TIME DECISION SUPPORT FRAMEWORK

5.5.1. Planning and control of a mine production system

This section analyses the proposition of developing an improved mine decision support (DSS) for a typical trackless mine operation. A DSS is described as a system that aids people in making better decisions and must be a computer-based system since a lot of data would need to be processed and presented as information useful for making decisions.

A mine DSS operates in the same manner as any manufacturing operational decision system. The envisioned operational concept of the real-time decision system in a typical underground mine needs to involve interaction of different control loops in a hierarchically organized manner for the mine as would typically happen in a manufacturing system.

The model of a mining decision system can be depicted as in Figure 5.7 adopted from Rembold, et al (1993) showing the decision and the information system structure at the different tiers of a typical mining organization.

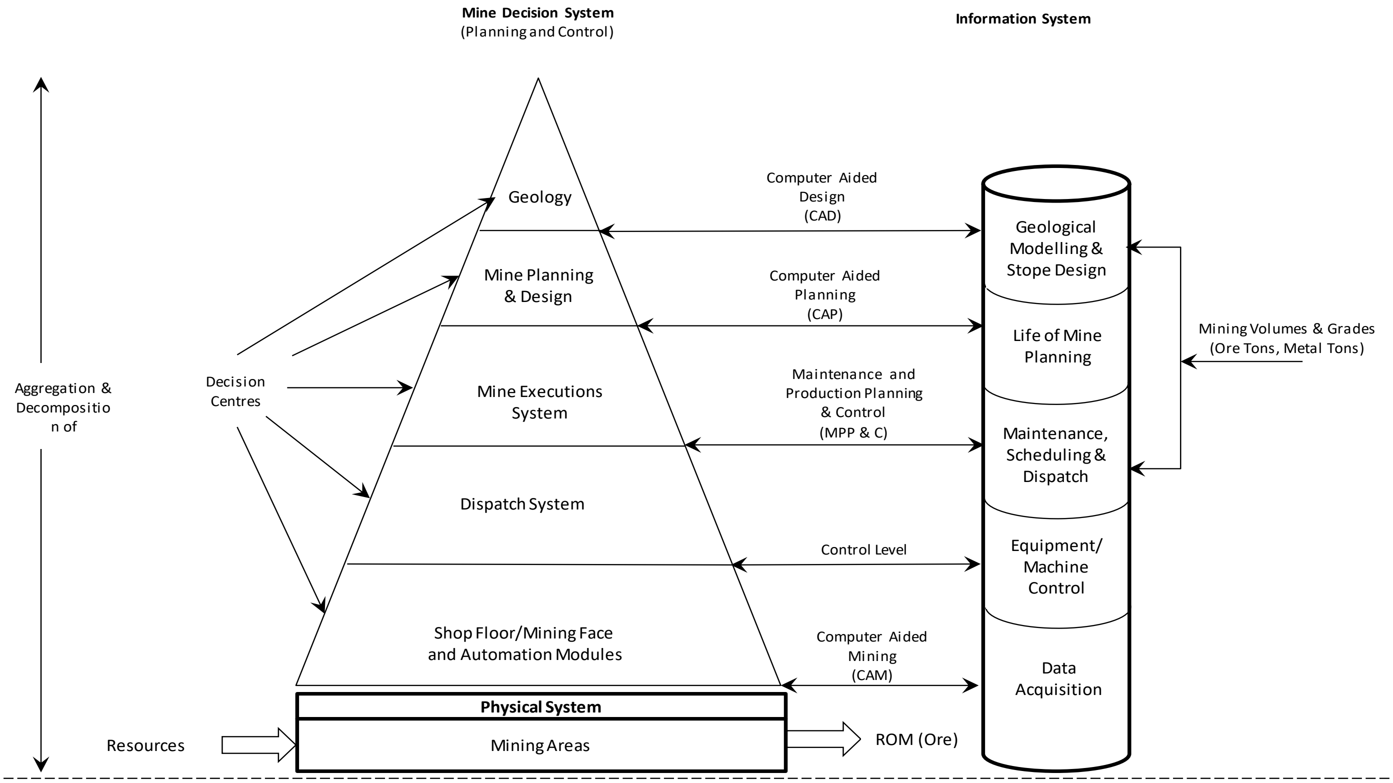


Figure 5.7 – Concept of a trackless mining planning and decision system (adapted from Rembold, et al (1993))

A mining system must be well planned and controlled for it to be competitive and extract value for the stakeholders. Rembold, et al (1993) explains that during the planning phase business is concerned with the future of the business while the control function concerns itself with the present of the company. These two functions must be well coordinated to ensure that the business goals and objectives are met.

Four critical areas which need detailed planning and control for an underground mine are around personnel dispatch, trackless equipment dispatch, equipment operation and equipment maintenance. A lot of value in the mine is eroded due to poor decision making around dispatching, operating and maintaining the equipment.

These four areas are interlinked and constitute most of the losses in the mine. The operational planning level of the organization which will include the maintenance and mining and equipment scheduling plans is central to the success of the whole mine plan because it integrates all the business, technical, planning and operational requirements of the business.

In practice, such a system can be realized through a mine operation execution system (MineOps), normally called as a manufacturing execution system (MES) in manufacturing context. The MineOps system will integrate the Mine planning and stope design system, with the production planning/control system, computerized maintenance planning and control (CMMS), the enterprise system ERP and the mining control dispatch system.

5.5.2. Context diagram for a trackless mine production system

To develop an effective control system for the mining process, it is important to understand the functions of the whole mining system. The system context diagram is an abstraction of these critical processes which interact in the mining processes and will interact with the envisaged decision support system. Fig 5.8 indicates a proposed context diagram in a trackless mine.

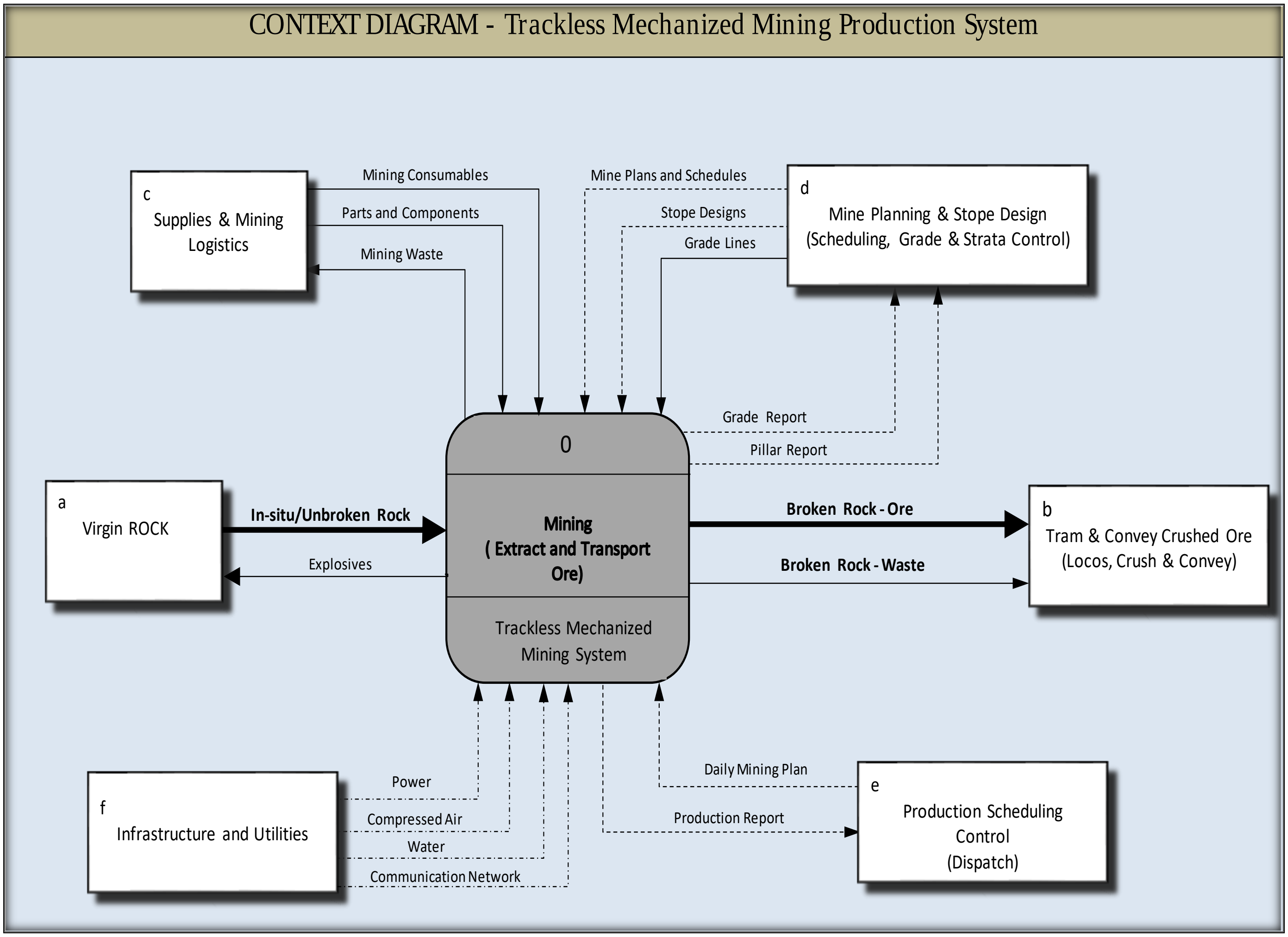


Figure 5.8 – Trackless underground mining system context diagram

The context diagram Figure 5.8 illustrates the major areas with influence to mining production are: the mine planning and stope design process, supply chain and logistics, production planning/scheduling and control process, Infrastructure and utilities, and people/personnel required and mining equipment. The decision support system (real-time) must influence the planning and control attributes of the system.

The analysis of the system commences by a hierarchical decomposing of the context diagram into lower levels which show the static and dynamic behavior of for the various activities which affect mining production. Figure 5.9 illustrates how the whole system is analysed showing an example of mining the ore.

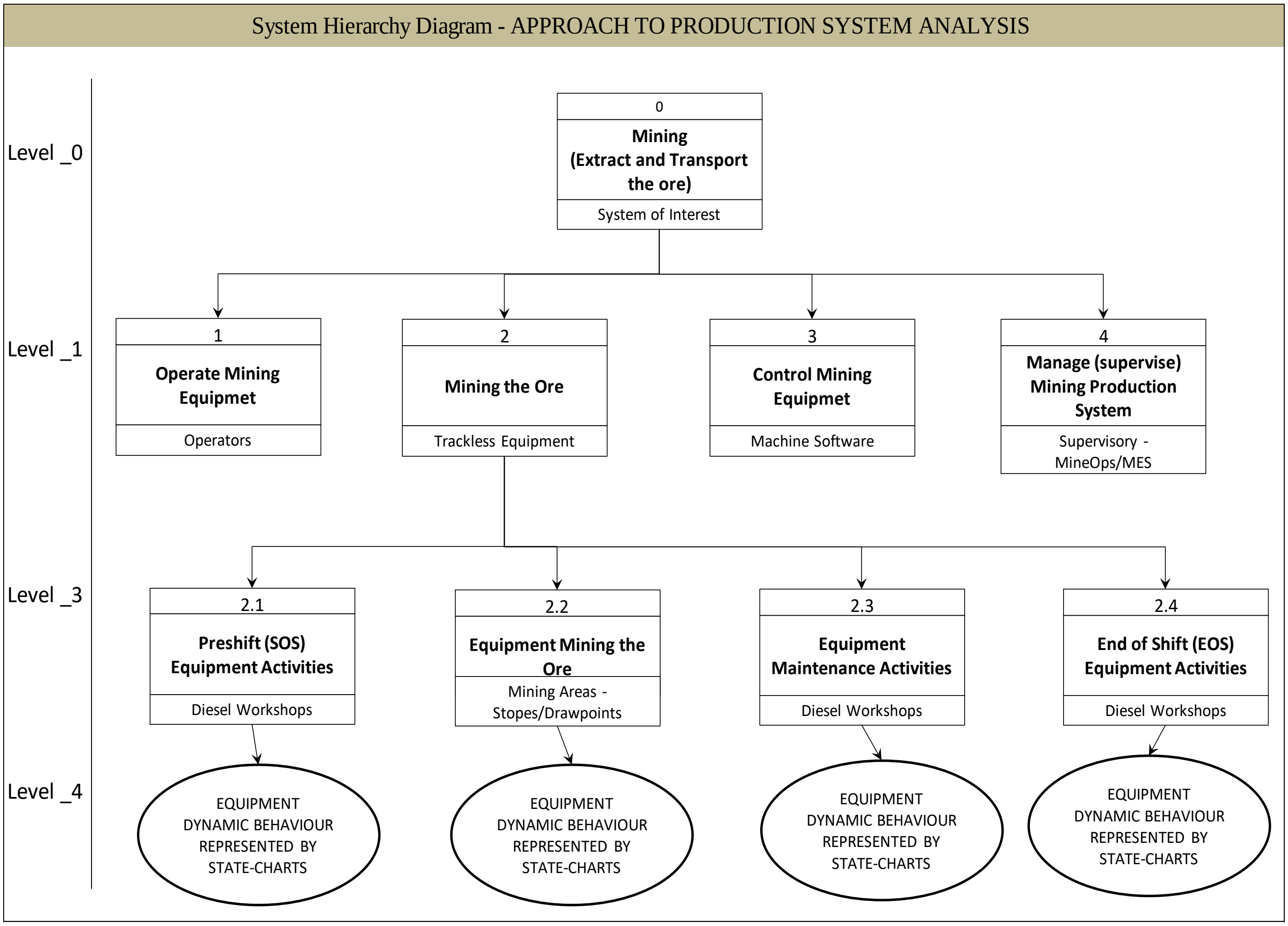


Figure 5.9 – System decomposition of Mining the Ore Context Diagram

5.5.3. Static and dynamic analysis of a trackless mining system

Based on the stakeholder feedback done in section 5.3, the system functional models were developed to show the static and dynamic activities of the mine production system through decomposition from Figure 5.9. These are the models that can be used to determine how a decision support system control can be configured, with real time capabilities.

5.5.3.1. System Static Models – IDEF0 Diagrams

The primary activities needed for Real-time control are hinged on processes for controlling and operating the equipment that is used in the mining process. A real-time decision system is directly linked to how operating and control is implemented in the system. A static model of a trackless system is illustrated in Figure 5.10 which is a decomposed from the system context diagram.

Figures 5.9 and 5.10 show how the activities of an underground mining shift system are divided into four level 1 sub-systems. These sub-systems are, (1) equipment operator subsystem which analyses all the operator's activities during the shift, (2) the actual mining activities being done by the equipment when operating, (3) the control function of the equipment software, and then (4) the supervisory role done by supervisor and any MES/MineOps systems installed at the mine such as the dispatch systems.

Process number 4 is about managing and supervisory control of these processes as they happen. The supervisory system (System-4) works through influencing the control and operating activities as they happen in real-time and is implemented through a manufacturing execution/mine operating systems such as dispatch systems

At the next level 2, basically all the activities in the sub-systems are all basically divided into five categories, being (1) start of shift (SOS) activities, (2) equipment maintenance activities, (3) equipment dispatch activities, (4) in-shift activities and (5) end-of shift activities (EOS)..

5.5.3.2. Dynamic Models – State Chart and Transition Diagrams

Dynamic behaviour of the activities is best analysed by further decomposing the level 2 static diagrams creating state charts and enhanced functional flow block diagrams (eFFBD). These two methods are used to illustrate the dynamic behaniour of the production processes. The state charts can be used in the development a real-time decision support controller.

Real-time supervision of the mining processes will include aspects of the machines actual functions, the machine control systems and the operator himself and the state charts will indicate the different states of these functions.

During the shift, there are different states of the equipment which influences the dynamic behavior of this process. Equipment may either be operating, be on standby or malfunctioning. Managing and supervising the production process involves getting oversight of the activities, functions and control of the equipment.

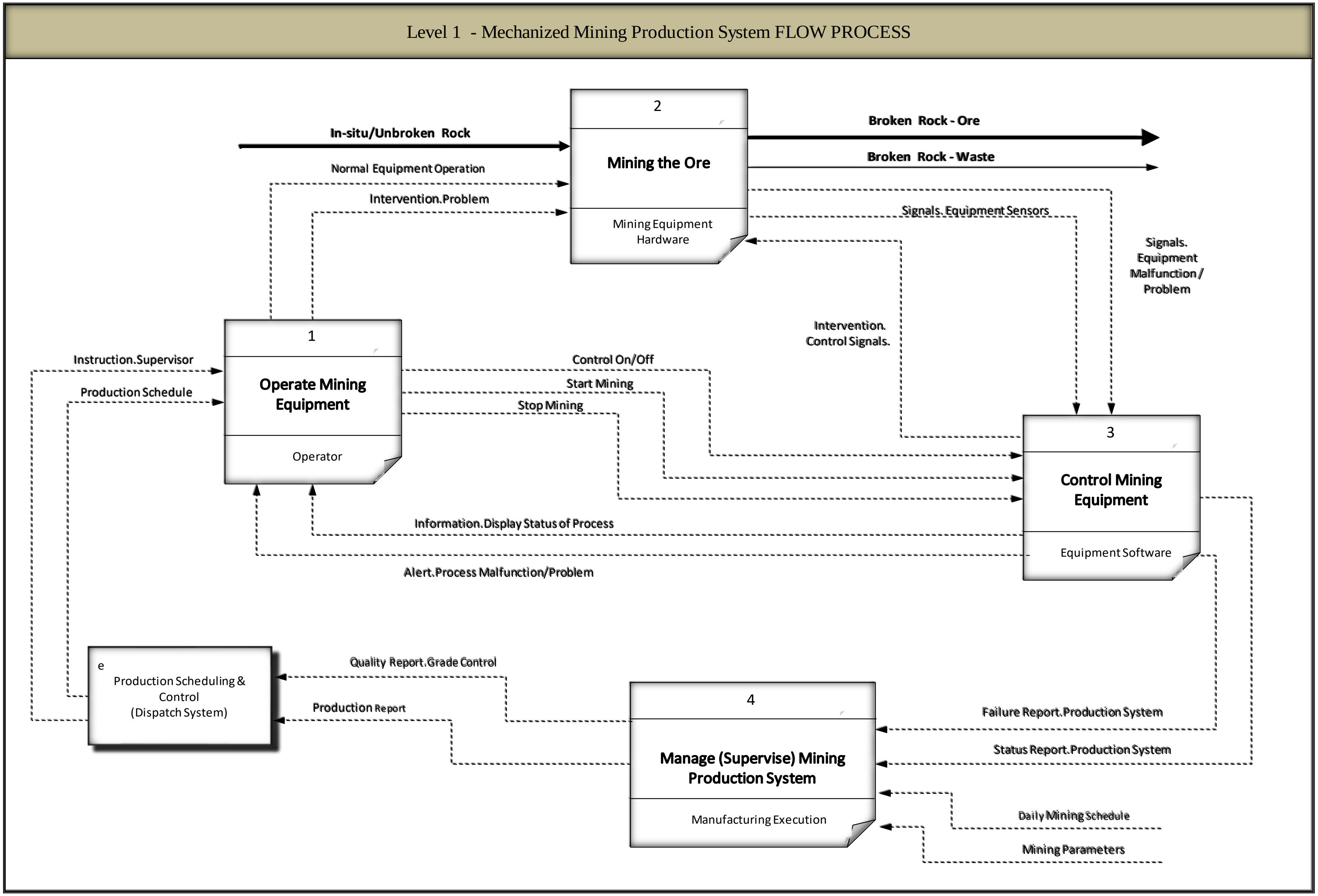


Figure 5.10 – Flow process for trackless production process

A decision support system (real-time) works by making all these processes visible to the decision makers as they happen. To set up the real-time model, development of static and dynamic models of the processes is critical. IDEF0 diagrams describe the structural or static nature of the process, while state charts, state transition charts and enhanced functional flow block diagrams (eFFBD) are used to define the dynamic behavior of these processes.

In the case of trackless system, the key processes hinges around the equipment operator, the equipment itself which performs the mining processes, and then the supervisory control system to manage and oversee the whole process.

The most important outcome of state chart analysis is the state transition lists. These state transition lists are crucial as they can be used to develop appropriate software to control the whole production process in real time. They are the specification lists which can be used by software developers in developing a practical decision support system (DSS).

5.5.3.3. Operating Equipment (Operator activities)

The first important process (Process1.0 - Operating Equipment), is the one that influences whether the production process is going to happen or not. Without the operators, even if the equipment is available there won't be any effective production. Fig 5.4 show the detailed activities which are performed by an operator during the different phases of the shift.

Effective utilization of the plant, to a greater extent, is influenced by the operator's activities. The IDEF0 diagram Figure 5.11 describes the various phases of the shift, while the state charts Figure 5.12 and state transition chart Appendix C1 describe the dynamic behaviours of a typical operator in an underground mining system during the different phases. The different colours in the state chart reflects the different shift phases.

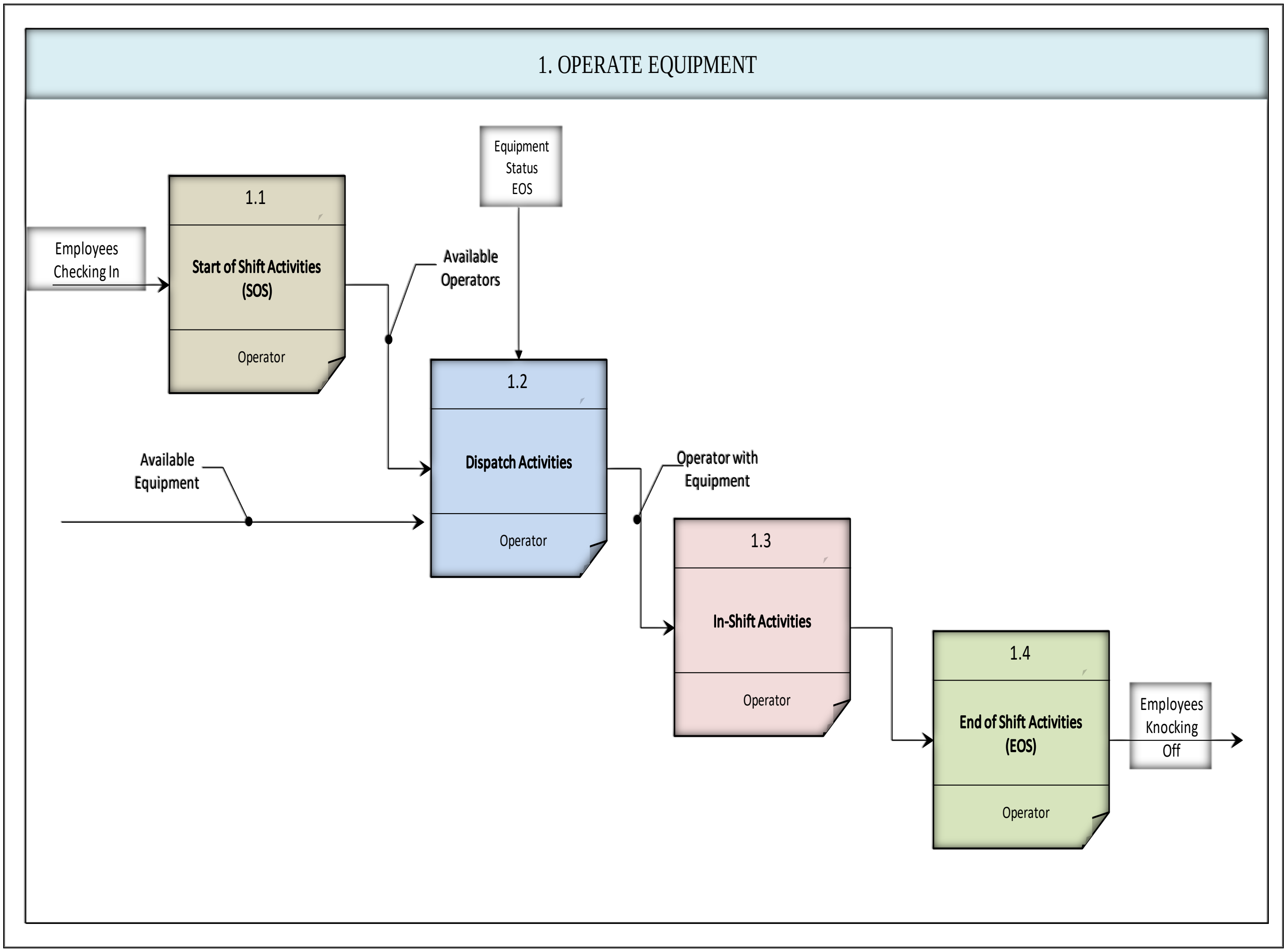


Figure 5.11 – Flow process for operating trackless equipment

About 11 dynamic states are identified for an operator during the different phases of the shift. The first state 1.1.1 is when the operator is not available. This could be because shift changeover at start or end of shift or it could be the operator is absent, on leave or is late to come to work. The states 1.1.2, 1.2.1, 1.2.2 and 1.2.3 are the activities which are linked to the operator travelling and preparing equipment for start of work.

A lot of delay is normally associated with these activities which include time at the waiting places where safety meetings are held and equipment allocations and checking of equipment is done. Activities 1.3.1, 1.3.2, 1.3.3 and 1.3.4 indicates the different dynamic states during the shift when equipment operation is actually taking place. Dynamic state 1.3.1 is the actual value adding activity where real mining work is taking place and is very important to maximize this state in operation.

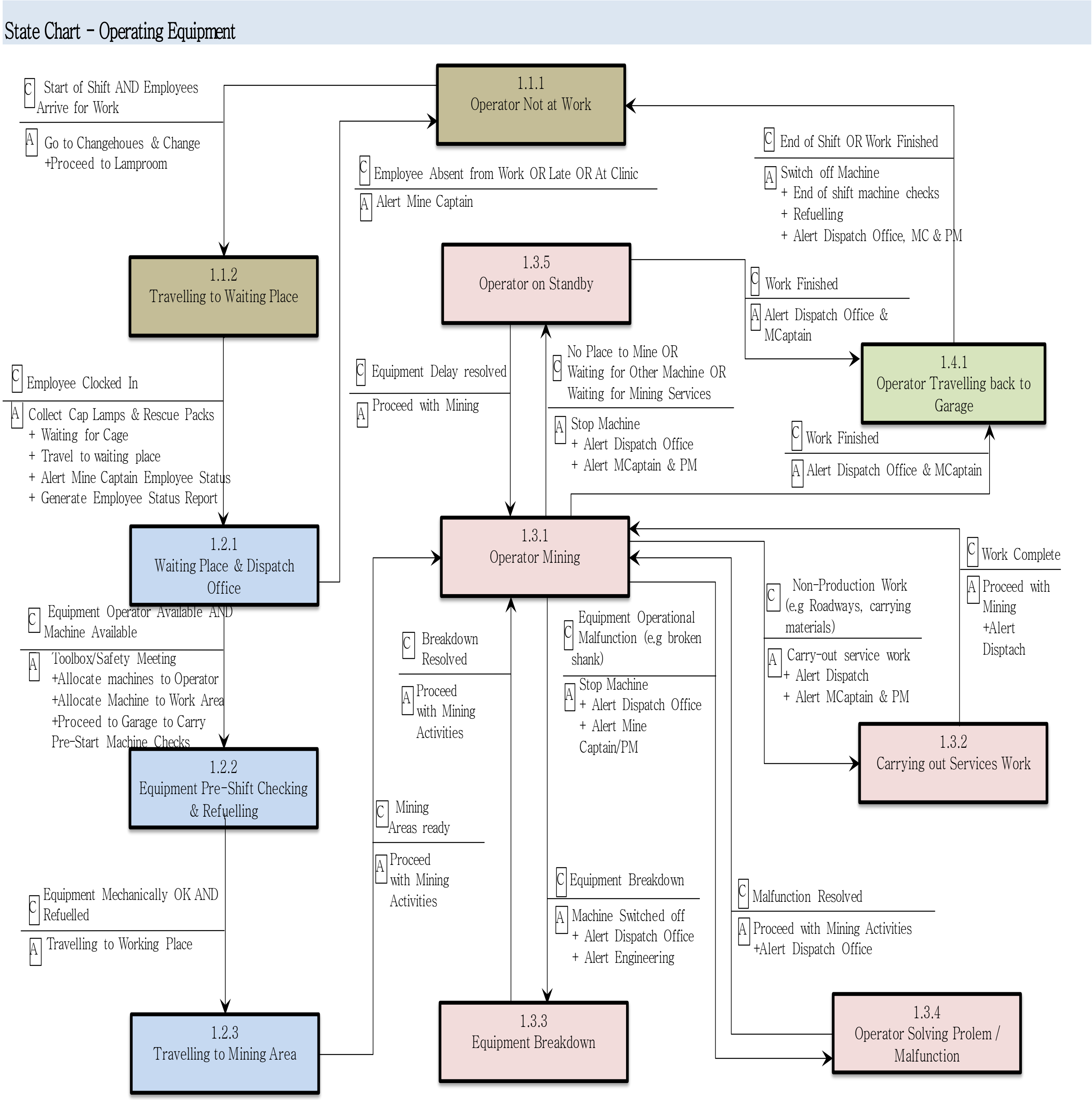


Figure 5.12 – State chart diagram for operating trackless mining equipment

The operating equipment state transition list is shown in Appendix C1 for clarity. A state transition list is an important indication of the actions and decisions that are taken to transition from one state to the other.

A certain condition presents itself and cause a certain action to be taken and the state transition list Appendix C1 shows who takes the action in the current situation. Some of the key transition actions include when equipment is on breakdown, when machine is on standby and when machine is not doing value adding activities.

5.5.3.4. Mining the Ore (Equipment Processes)

The next important functions are those performed by the equipment itself as depicted by Figure 5.13. In these processes, the actual mining activities are carried out by the equipment, i.e., the actual plant or machine. Critical activities in this process are those activities which have to do with making the equipment available for use, followed by the actual use of the equipment during the shift to produce the ore.

5.5.3.4.1. Pre-Shift Maintenance Processes

Pre-shift maintenance work starts by the machines being checked by the mechanics before they are released for work. Usually the safety functions of the machines are checked first such as brake tests, steering, lights, electrical safety interlocks together with lube checks. Normally after this the machine is ready for production, or else if further corrective work is required the machine is now declared to be in a breakdown mode.

5.5.3.4.2. Mining the Ore (Equipment Processes)

This process presents the dynamic states of the machines when the machines are performing the mining operations after pre-shift maintenance work. During this phase, equipment may either be off, on standby, carrying out the actual mining, production delays (such as no diesel, bits worn out, etc.) or diagnosing equipment problem. These various phases and states are depicted in state fig5.8.

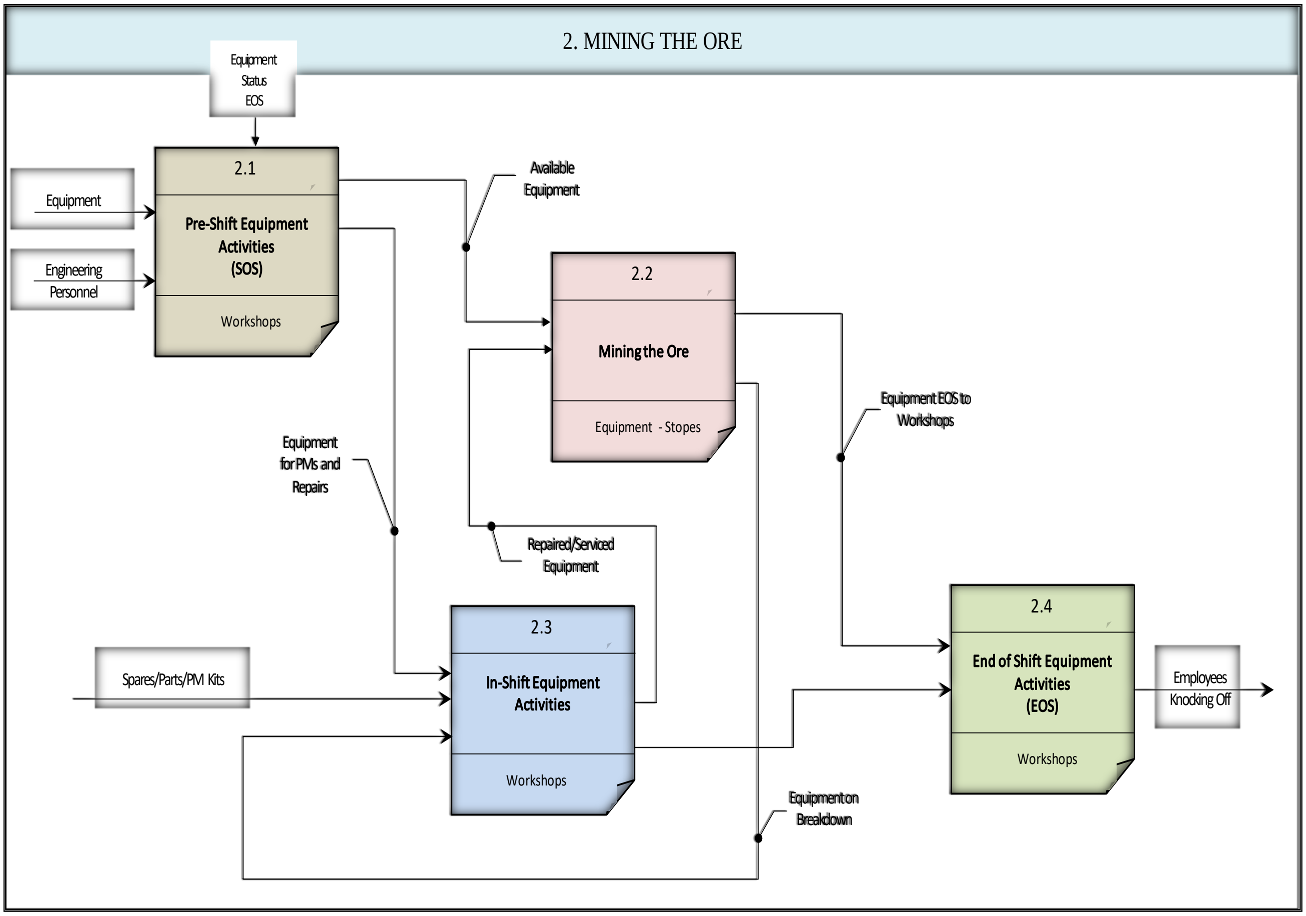


Figure 5.13 – Process flowchart for mining process

5.5.3.4.3. In-shift equipment maintenance activities

These are the dynamic states when the machine develops some problems and need to be attended during the shift. This also involves planned maintenance activities (PMs) which will have the machine in an off-state as planned work is being carried out on the machine.

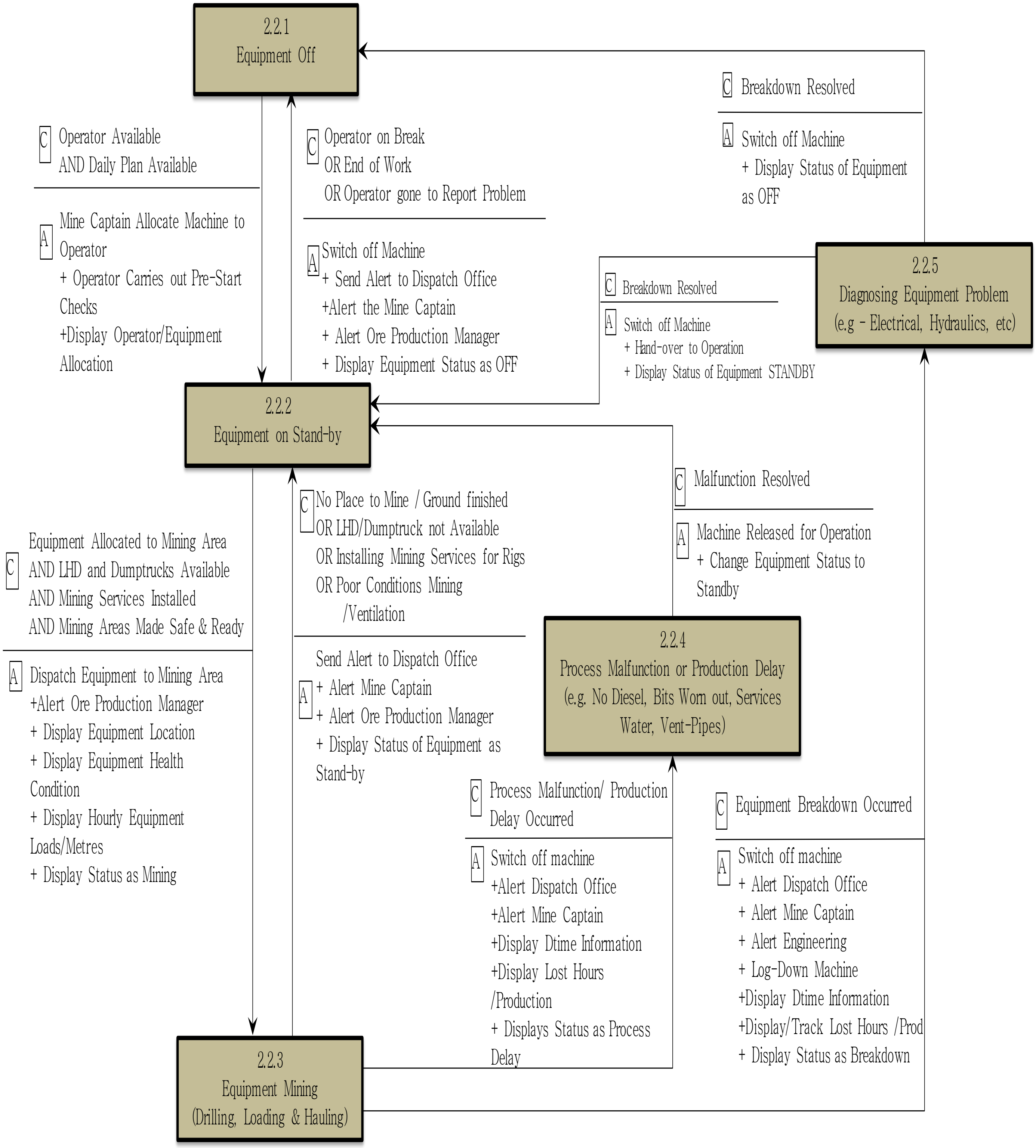


Figure 5.14 – State chart for mining ore

A state transition list for mining in-shift activities is given by Table 5.5.

State Transition List - MINING OPERATIONS IN-SHIFT ACTIVITIES				Current Functional Roles		
Original State	Destination State	Condition	Action	Operator Role	Supervisory Role	Contol & Information Role (Manual)
4.4.1	4.4.2	Start of Shift & Operator Available	Mine-Captain allocates machine to Operator		x	
			Operator Carries out Pre-Start Checks	x		
			Display Operator/Equipment Status Information			
4.4.2	4.4.1	End of work, or Operator on break, or Operator not at Work or Operator to gone to report breakdown	Switch off machine	x		
			Report to Dispatch Office	x		x
			Alert Mine Captain and Production Manager		x	x
4.4.2	4.4.3	Equipment Allocated to mining area, and LHD/Dtruck/Drill Rig Available, and Mining Services Installed, and Mining Areas made Safe	Dispatch Equipment to Mining area		x	
			Alert Production Manager and Mine Cpatain			
			Display Equipment Loaction			
			Display Equipment Health Status			
			Display Hour by Hour Equipment Loads/Metres			
			Display Shift Production Status			
4.4.3	4.4.2	No Place to Mine/Ground finished, OR LHD/Truck/Drill Rig is not Available, OR Installing Mining Services OR Poor Mining Conditions/Ventilation/Gases	Send Alert to Dispatch Office	x		
			Alert Mine Captain and Production Manager	x		
			Mine Captain Issues Instruction for new area to Mine		x	
4.4.3	4.4.4	Process Malfunction / Production Delays Occurred	Switch off machine, and	x		
			Alert Dispatch Office, and	x		
			Alert Mine Captain and Production Manager	x		
			Mine Captain Issues Instruction for new area to Mine		x	
			Display Downtime Information, and			x
			Display Lost Production Hours			x
4.4.4	4.4.2	Delay Resolved and Machine Released to Production	Change Equipment Status to Standby			
4.4.3	4.4.5	Equipment Breakdown Occurred	Switch off Machine, and	x		
			Alert Dispatch Office, and	x		
			Alert Mine Captain and Production Manager	x		
			Alert Engineering Office	x		
			Log Down Machine and Display Downtime Information			
			Display/Track Lost Production Hours			
4.4.5	4.4.1	Breakdown Resolved	Switch off Machine, and	x		
			Hand-over machine to Operations		x	
			Display Status of Machine as Off			

Table 5.5 – State transition list for mining process

5.5.3.5. Equipment maintenance activities

Equipment maintenance activities are very key to the survival and success of a mine production system. Figure 5.15 show the various dynamic states of equipment when under maintenance and Appendix C2 shows the state transition list for equipment maintenance. The state transition chart Appendix C2 show the interface activities that go on between the various machine states.

There are four dynamic states of a machine when under maintenance. The first one is when machine pre-shift checks are done by mechanic. This activity involves statutory checks on machines each shift to check mostly the safety features of the equipment before use. The second state is when machine might be under planned preventative work. Planned preventative works is a key requirement for ensuring the integrity of operating equipment.

The third state of a machine is when it is might be under corrective repair work. This corrective work involves emergencies such as breakdown and work that might be needed to restore machine as quickly as possible due to production. In some situations, corrective work is planned and is done on a planned work

The fourth state is when machine is on longer outages due to major repairs or overhauls. Various key decisions need to be made in each state and good planning is very key to success.

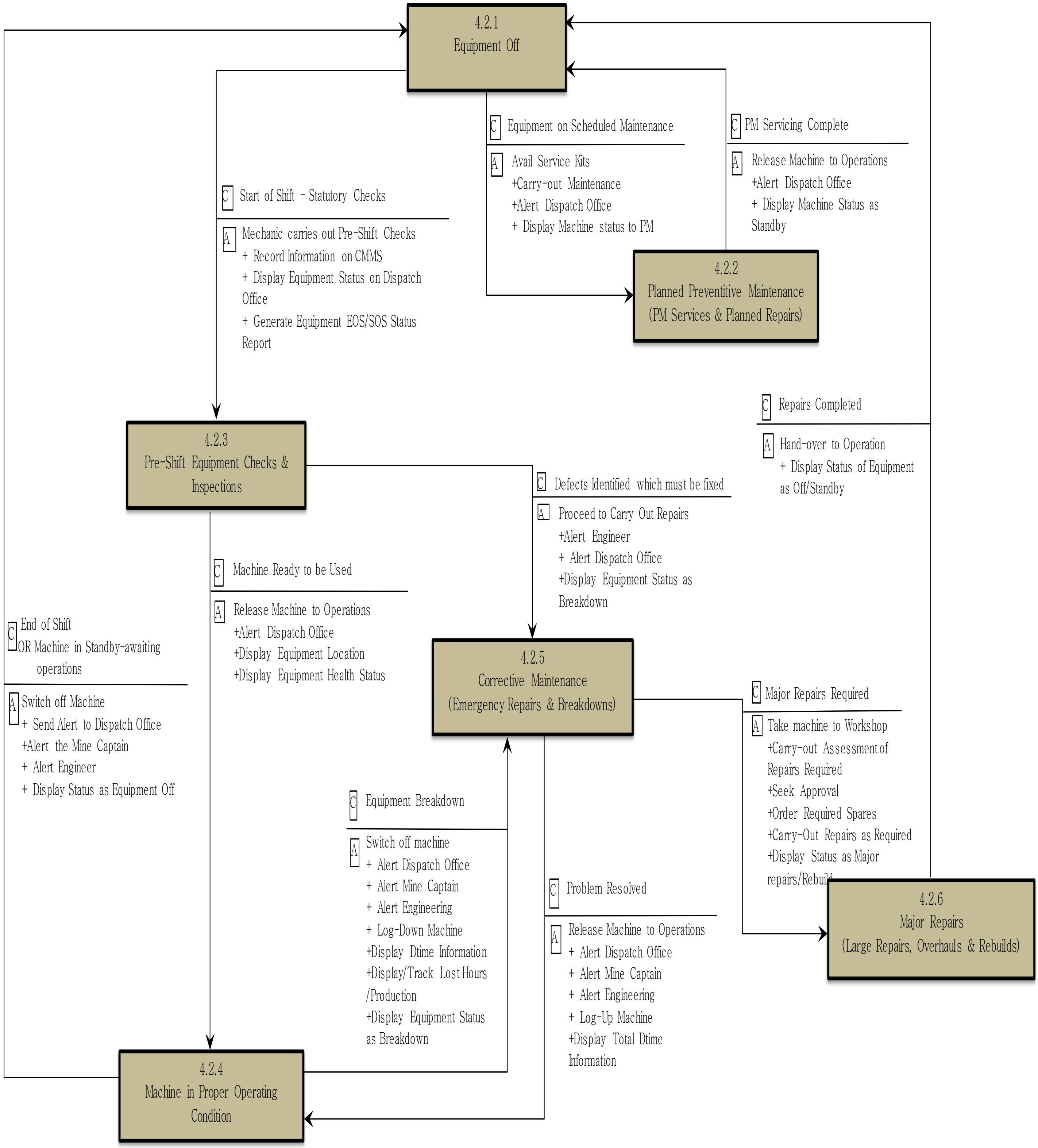


Figure 5.15 – State chart for Equipment Maintenance Activities

5.6. PROCESSES FOR MANAGING AND CONTROL OF TRACKLESS OPERATIONS

This process provides the supervisory oversight on the operations and thus gives directions and control to control deviations during the shifts. Control of the operations is basically hinged on controlling the start of shift activities, the dispatch of equipment, equipment maintenance and the activities during the shift which are expected to be value adding. Figure 5.16 shows the process.

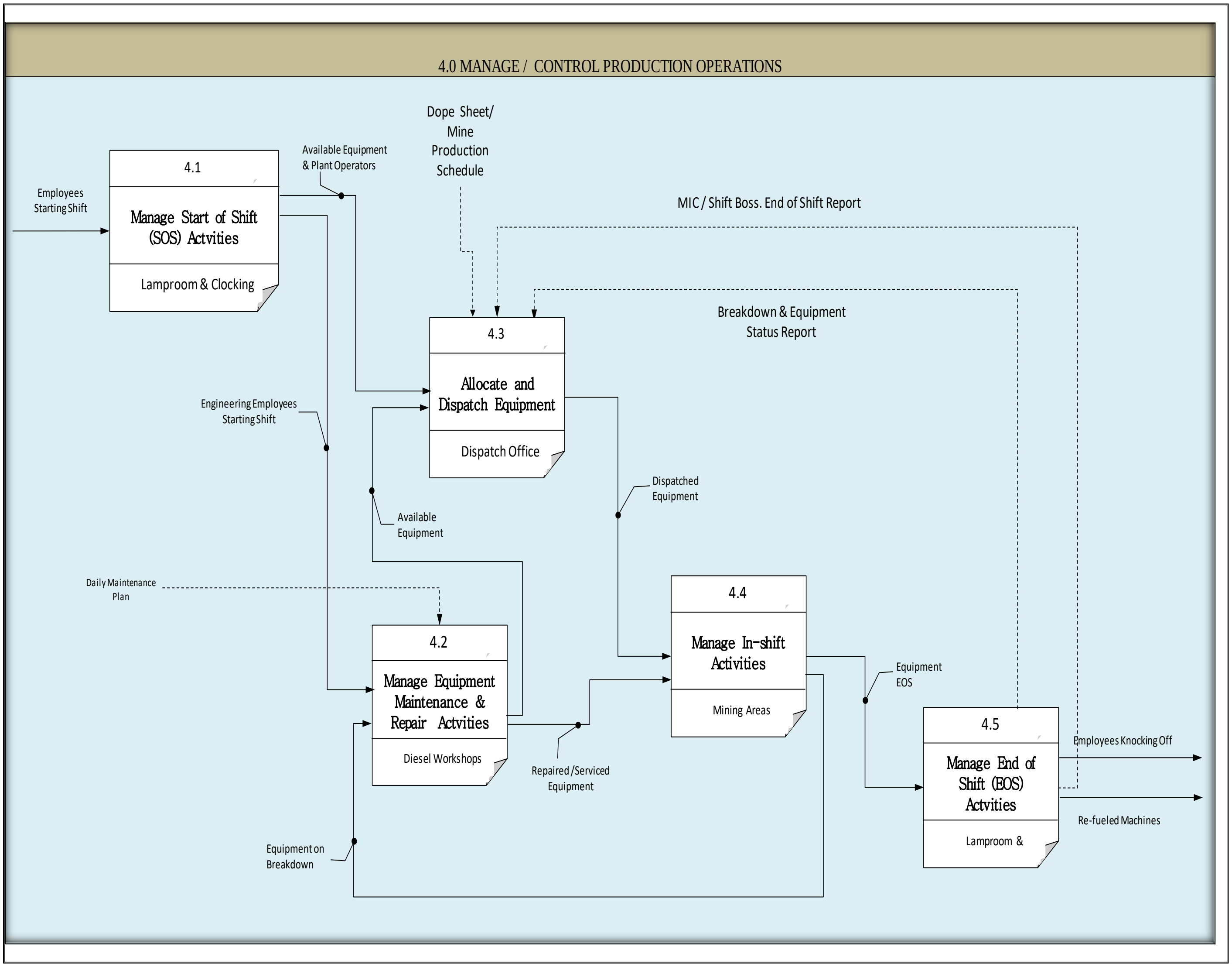


Figure 5.16 – Process flow diagram for supervisory control of operations

The dynamic diagram for the operational control processes is given by an eFFBD Figure 5.17, which illustrates the key dynamics of the activities which take place during a shift, being basically the maintenance and repair activities, the dispatch of equipment and the actual mining activities.

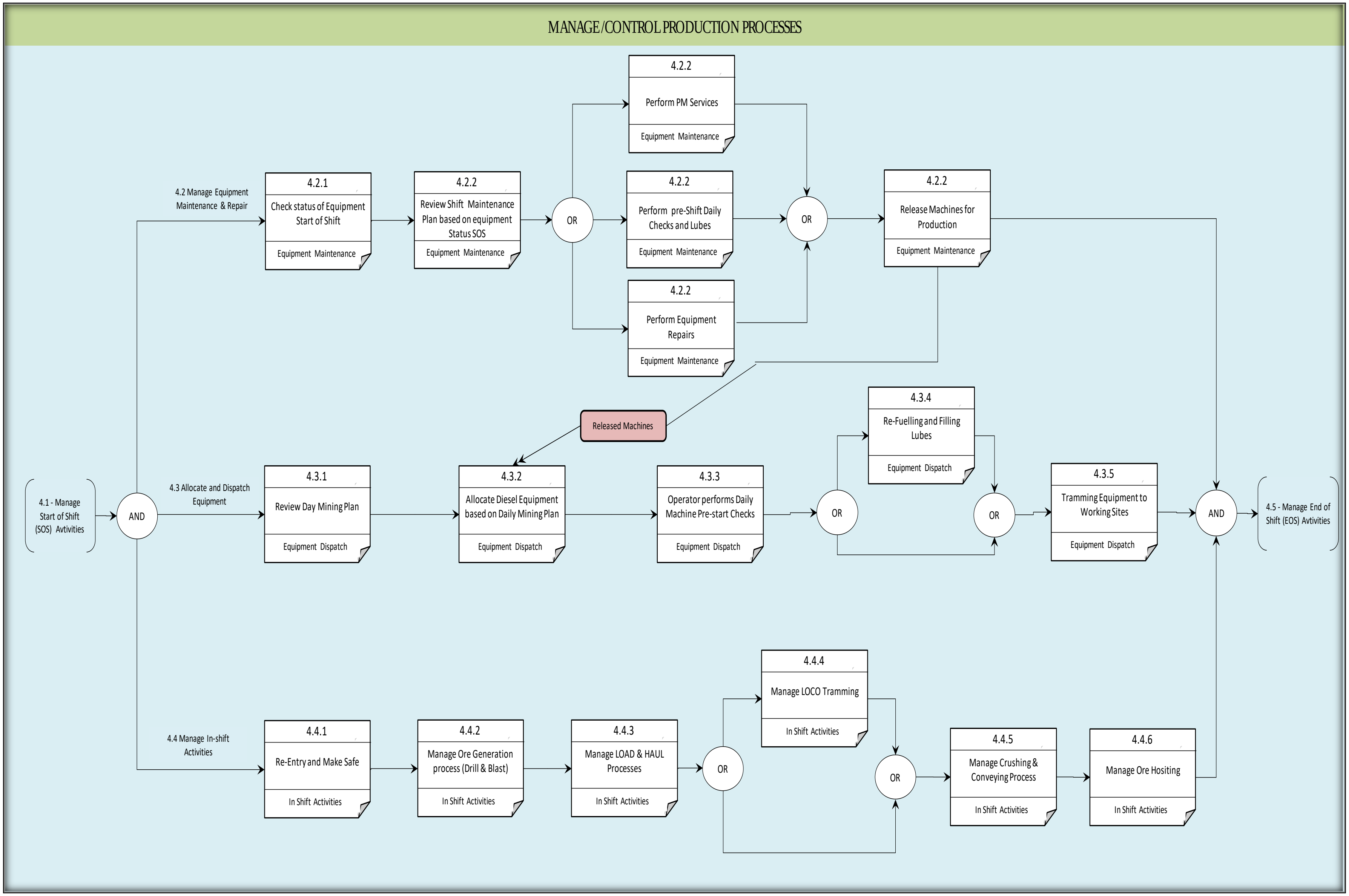


Figure 5.17 – eFFBD for dynamic control of the production operations

5.7. CHAPTER CONCLUSION

This chapter illustrates how an activity analysis can be done for a trackless mine production system, stating with the context diagram, the process flows and the state charts/transition lists. This type of analysis has advantages that the interacting behavior of each activity in the various dynamic states of the process can be fully analyzed.

From an observation and a brainstorming session with key stakeholders in the production process, a list of 52 critical activities were listed as the key activities on a day to day in the mine. These activities were then ranked by importance of those that had greatest impact to production. From this listing, IDEF0 diagrams were developed to. The IDEF0 diagrams were key to dynamic analysis of the system behaviour during operation. State charts and eFFBD were then used to analyse the dynamic behaviour of the system.

The final outputs from this analysis are state transition lists which can be used to configure a decision support system. Chapter 7 gives details on how value can be unlocked through making all the activities visible through a real-time control system using the input from the state charts and state transition lists.

6. ANALYSIS OF ARCHITECTURE INTERFACES FOR UNDERGROUND DSS

6.1. CHAPTER OVERVIEW

The overall purpose of a decision support system (DSS) in an operational system is to allow rapid decision making especially at shop floor level so that waste is minimized. In the context of an underground mining system, an improved DSS must enable quick decisions to be made at the face preferably in real-time due to the impact that wrong decisions will have on the whole process. This therefore entails a communication infrastructure which can support real-time capabilities.

This chapter is an analysis of how an improved DSS for underground is configured and operates, after identifying the critical functions in Chapter 5. The first part of the chapter discusses describes the various configurations and protocols used in designing a communication system. The ISO open systems interconnection (OSI) model and manufacturing automation protocols (MAP) which can be applied in the development of a functional DSS for underground are explained and discussed. This section looked at how a communication architecture can be designed and the public guidelines and protocol that are available.

Next section looks at the result of the online survey which was done which looked at how the concept of decision support systems have developed in African context. The analysis looked at possible opportunities available to apply improved technologies.

The final part of the chapter looks at mapping of the actual physical system as observed at *MinePQR* which operated an active real-time dispatch system.

The chapter is thus structured as below:

6.2. COMMUNICATION NETWORK AND PROTOCOLS FOR UNDERGROUND

A real-time decision support system can only be made possible by a communication architecture which can support such a system. For an underground mining system, this is a growing area where a lot of research work is going on including development of appropriate communication standards and protocols for underground. However, it can be shown that systems which give real-time support in underground systems are already being implemented using technologies such as leaky feeder systems, optical fibre and ethernet and supporting local area networks and wide area networks for baseband, broadband and frequency division multiplexing systems (FDM).

The ISO/OSI protocols and models have been adopted in the manufacturing industries for enabling different devices from various manufacturers to be connected so that they can communicate with each other to enable information to be passed between the different devices through local area networks (LAN) or wide area networks (WAN).

A simple LAN communication system is described as below in Figure 6.1

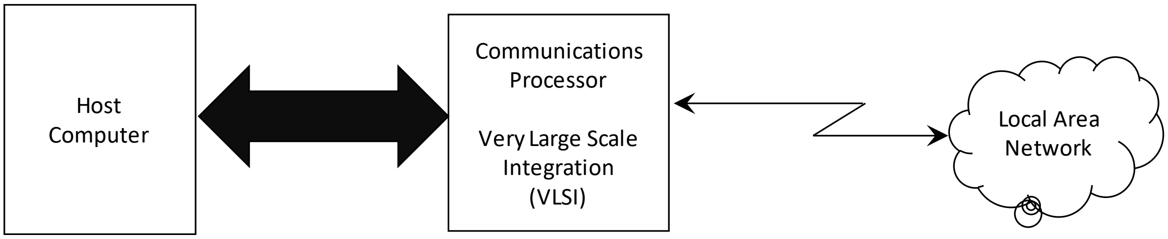


Figure 6.1 – LAN communication system (adapted from)

The ISO/OSI open system communication models specifies a 7-layer model in the design of computer networks whereby the computer systems are organized as a series of layers or levels, each one build upon its predecessor with the purpose of each layer offering services to the higher levels.

The first 3 levels provide the network services while the upper layers provide application protocols for information processing

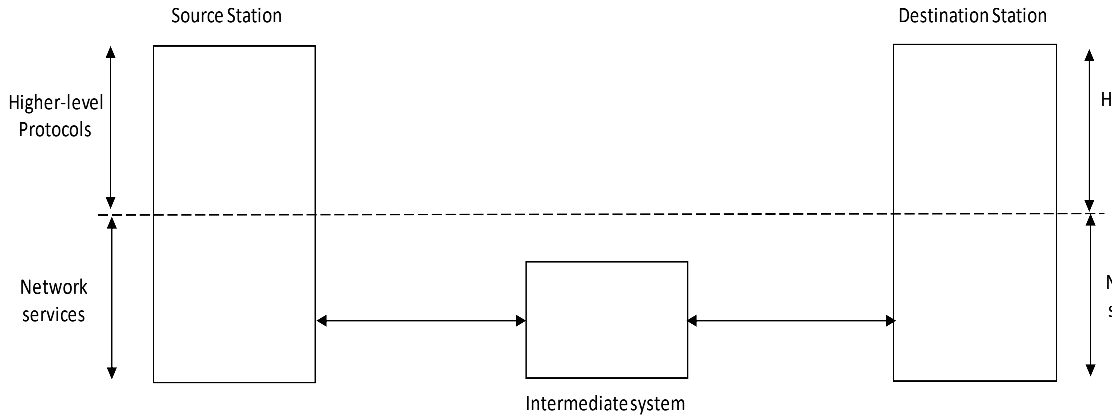


Figure 6.2 – ISO/OSI open system communication models

The function of the seven layers in the OSI model are described as below

Layer		Function of Layer
7	Application	Application-specifica processing (e.g. Manufacturing Automation Protocols (MAP))
6	Presentation	Information represantation and transformation
5	Session	Dialogue management between applications
4	Transport	Error and flow control between end systems
3	Network	Routeing, switching and inter-network control
2	Data Link	Error, link management and medium access control
1	Physical	Bit transfer and signalling - physical interface between devices covering mechanical, electrical, functional and procedural characteristics of physical connections.

Table 6.1 – OSI Communication model layers

The diagram Figure 6.3 describes the OSI protocols and how the different layers are interlinked. Layers 1, 2 and 7 are the most important layers from the user's point of view for most intends and purposes, which is the physical, data link and the application layers.

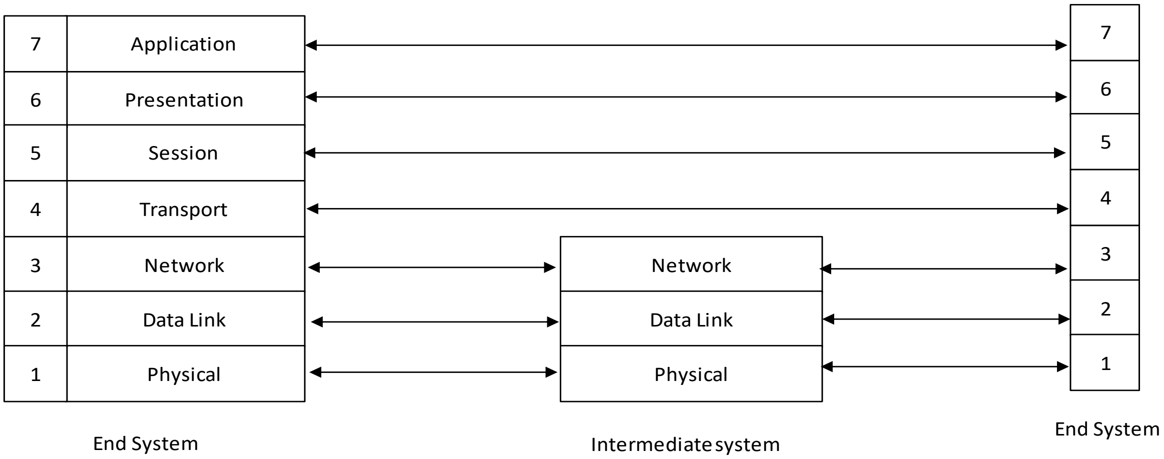


Figure 6.3 – Communication structure of OSI model

The general arrangement of a communication system in a mine can thus look Figure 6.4

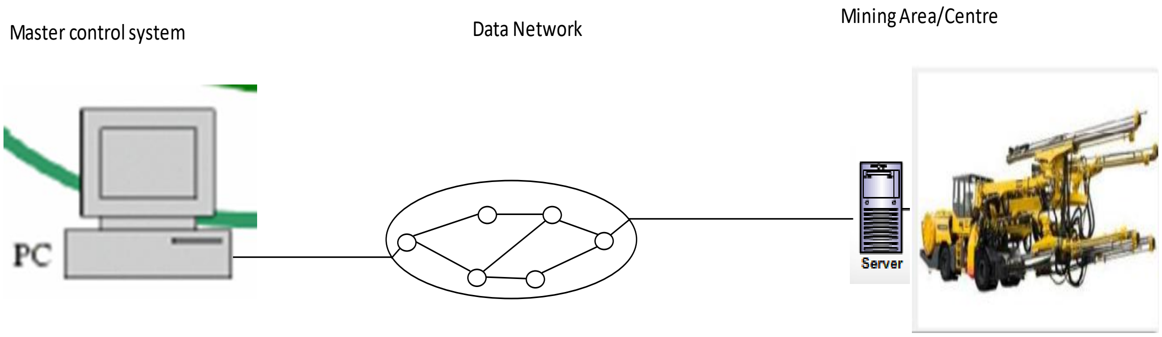


Figure 6.4 – Structure of a mine communication system

In modern communication systems, the communication systems for a complex system like an underground mine are being improved using the concepts of Field-bus. The field-bus is a digital replacement of the 4-20mA interface which is widely used in industrial process control with a bi-directional digital communication system.

The field bus system has an advantage that it can be used with varied communication media such as twisted pair, coaxial cables, screened co-axial cable, fibre optics and radio communication, including simple messaging protocols including MAP protocols and where a distributed control system is required.

It can also be used with various topologies as illustrated Figure 6.5 which makes it suitable for underground systems which requires a flexible topology because of the complexity.

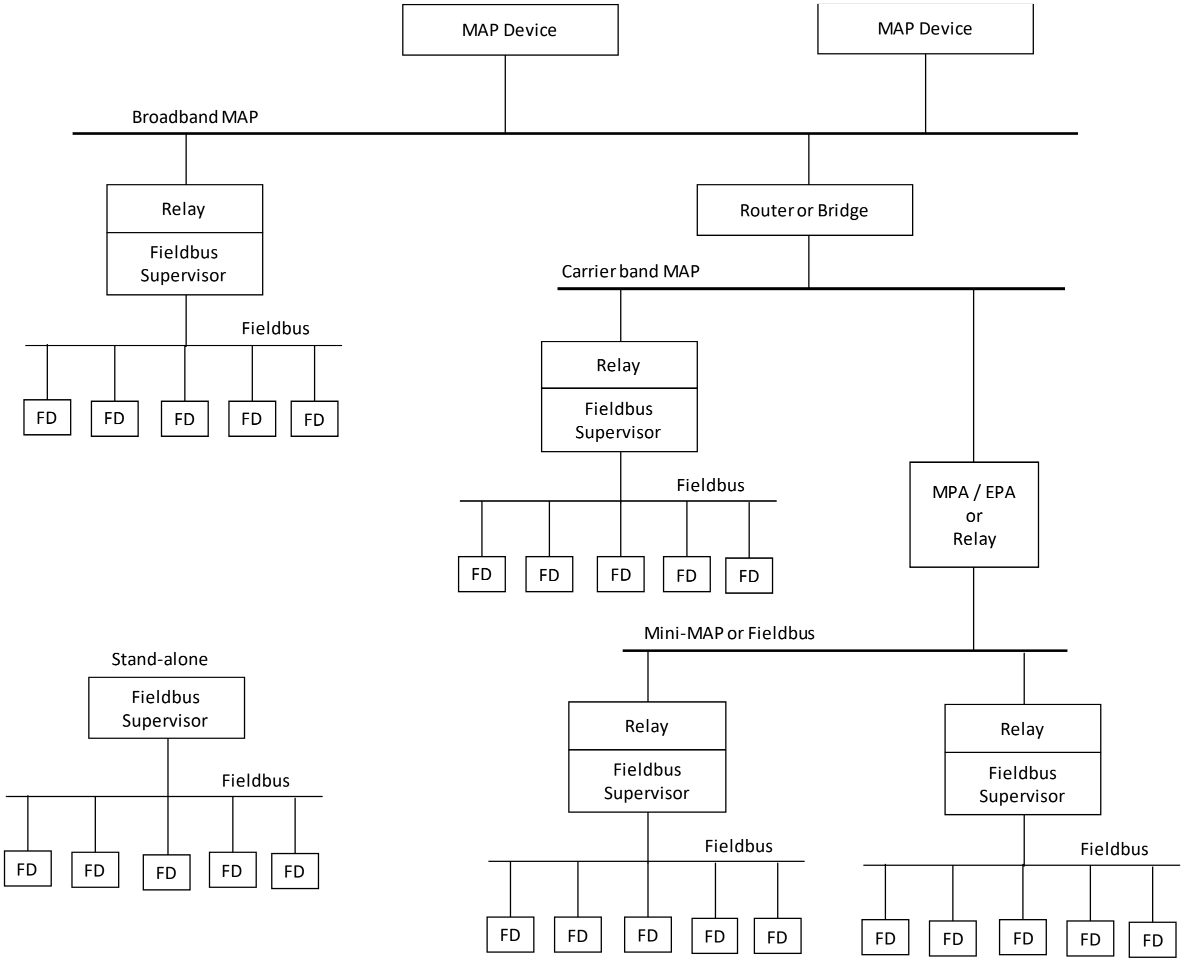


Figure 6.5 – Manufacturing Automation Protocols (MAP)

The MAP protocol can be represented in by Figure 6.6 below which illustrates a hierarchical computer and sensor system for planning and controlling the manufacturing operations.

Figure 6.6 below depicts the conceptual architecture of the overall DSS based on the MAP protocol

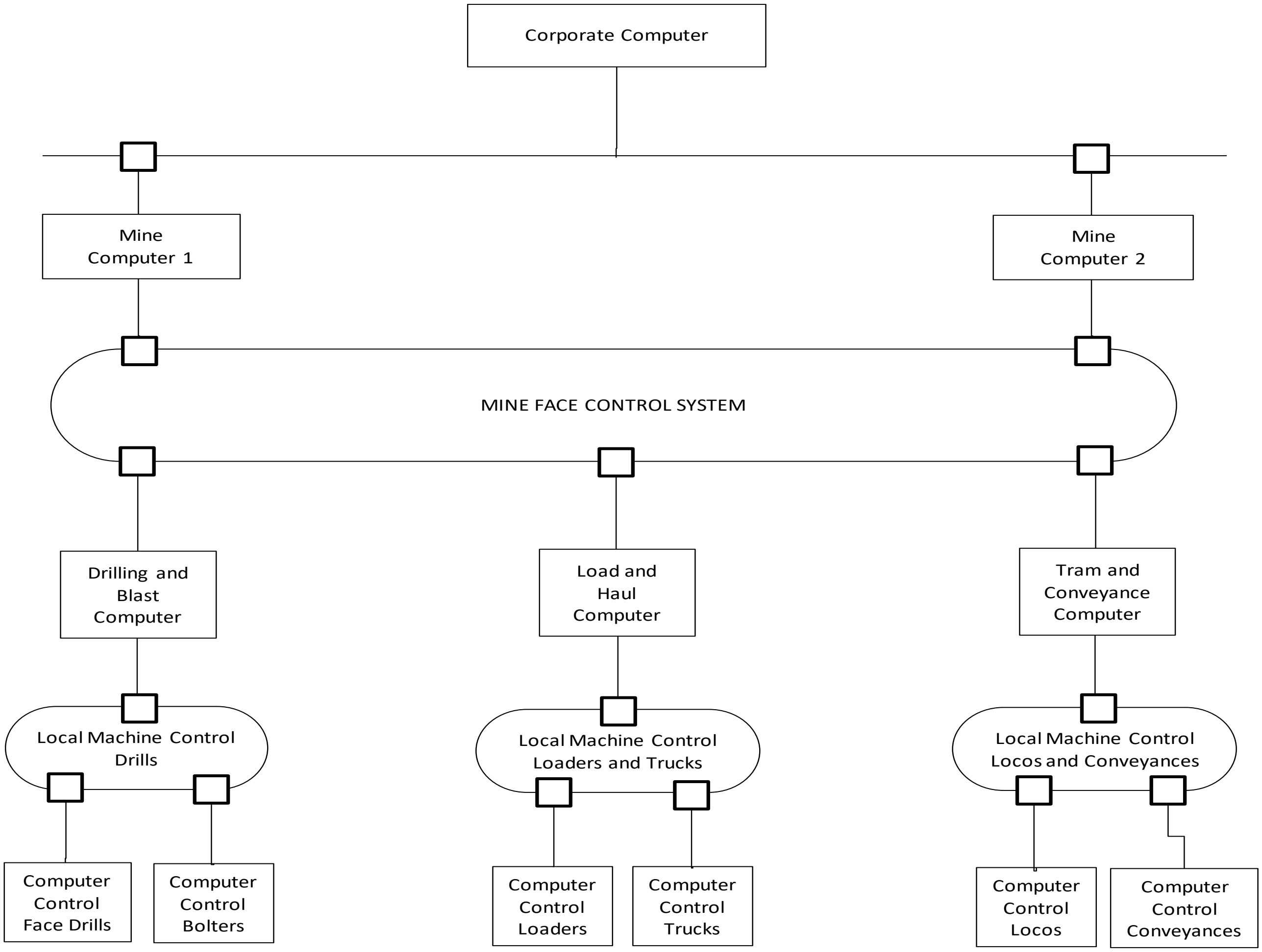


Figure 6.6 – Possible arrangement of a mine computer control system

The physical layer of such a system can be mapped from the input output diagram as shown Figure 6.7. An active information processing system for underground will consists of various input peripherals such as portable terminals like hand held phones, videos, RFID tags on machines and cap lamps among others.

The output may include hand held terminal, end user access terminals, amplifiers and telephones. A mining control room is a key part of the input/output terminals. Various key outputs from a decision support centre include visual displays, trending charts, data visualizations, geological maps and charts, etc.

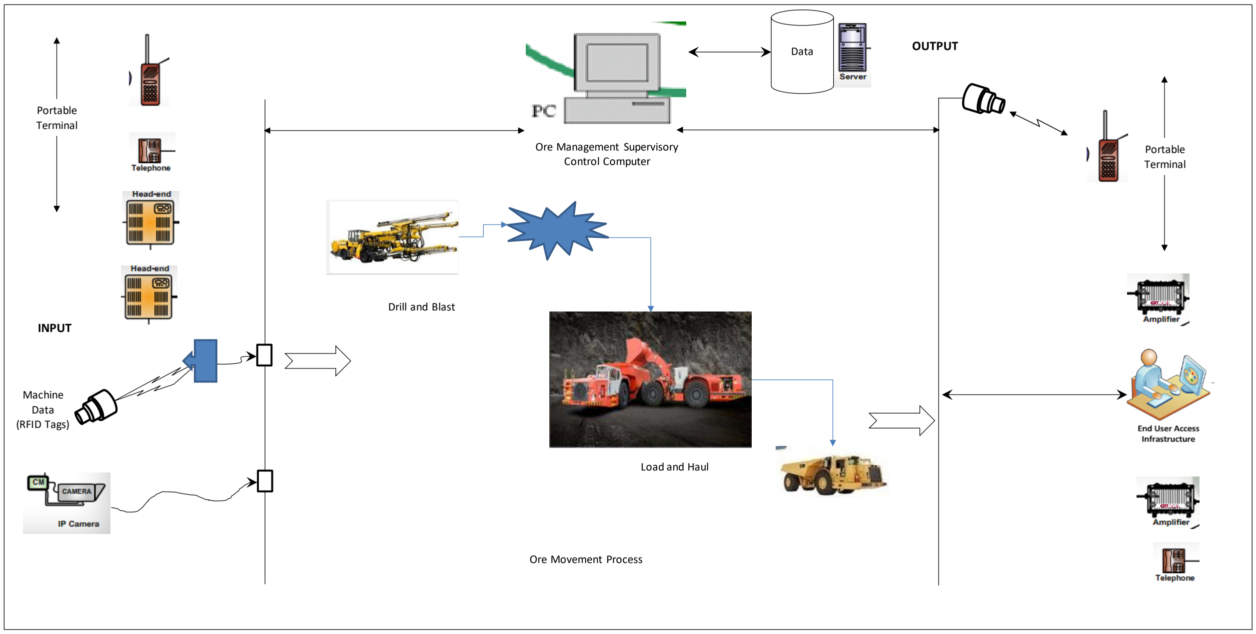


Figure 6.7 – Input and Output configurations for mine control systems

Figure 6.8 – A potential mine operations control centre configuration (images source: Sandvik (2016), and https://pixshark.com/future-control-room.htm. accessed 11 August 2018)

Section 6.3 is a test on how aspects of such technology have found applications in mining industries in developing countries. A survey of several mines in southern and western Africa was done to check this.

6.3. ONLINE SURVEY - TECHNOLOGY OPPORTUNITIES IN AFRICAN CONTEXT

6.3.1. Online survey scope

The concept of real-time and decision support systems is a current buzz word in different facets of the business world. Benefits of application in underground mining situations is currently a subject of many studies, as this concept is still novel in this area and a lot of research is currently ongoing.

With the aim to add more knowledge to this area, this study tested how far this concept has been applied in underground hard rock mines. The objective was to check whether there are opportunities that are available for implementing value adding opportunities in the African mining context. An online survey plus two detailed case studies were carried out to see what decision support technologies currently being used in some existing mines in Southern Africa.

The following areas were checked as the basic systems required In order to test if a mine has a capability for a real-time decision support system:

- Availability of an effective Enterprise Resource Planning system such as SAP at the mine
- Availability of an integrating Mine Operations Execution System/Manufacturing Execution System (MES) such as computer aided dispatch systems (CAD).
- Presence of a mine operations control centre(MCC).
- Availability of a communication backbone which enable realization of data, voice and video transmission.

6.3.2. Availability of integrated supervisory and operations monitoring systems

First area surveyed was the presence of integrated software which would enable implementation of real-time decision support system. The Table 6.2 is a summary of the findings in terms of ERP and MES systems being used at the different mines.

Software Systems and Real-Time Decision Support Technology

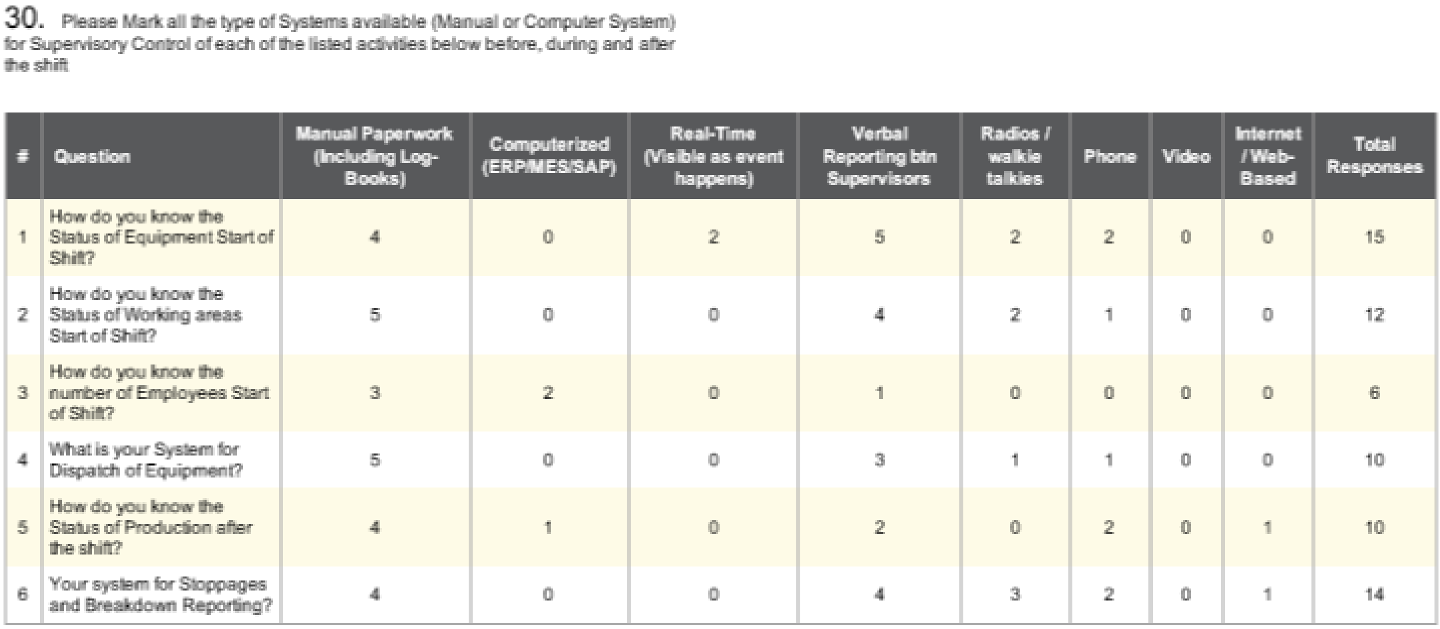
										Summary Results Analysis	
		Mine1 Zim	***Mine2 Zim***	***Mine4 Zim***	***Mine5 Zambia***	***Mine6 SA***	***Mine7 SA***	***Case Mine 1 Botswana***	***Case Mine 2 SA***	***Frequency of Occurance***	***Mode/Mean***
Q18	Type of ERP System in use at the Mine (SAP, MIMS, DELTA ERP, etc)	SAP	Excel	SAP	MIMS	Excel	SAP	**Delta ERP**	**SAP**	**SAP (50%), MIMS(12% Other(38%)**	**SAP**
Q19	Existence of an Operations Execution System / Operations Management Software in Place - Systems which integrates Mine Planning and Operations (MineOPs, RPM EXACT for Enterprises, etc)	No	No	No	Yes	No	Yes	**No**	**Yes**	**No (62%), Yes (38%)**	**No**
Q20	Existance of a Mine Operations Control Centre -Mission Control Centre /Control Room For Real-Time monitoring and tracking of operations underground	Yes	No	No	Yes	No	Yes	**No**	**Yes**	**No (50%), Yes (50%)**	**50/50**
Q21	When was a Mine Operations Control Room / Mission Control Centre Installed	1 year ago	None	None	1 year agc	None	> 20 yrs	**None**	**16 years**	**>15 yrs ago(25%), 1 ye None (50%)**	**50% No system**
Q22	Production Improvement in terms of Tons mined after installation of the Mine Operations Control Centre	5%	N/A	N/A		N/A	> 30%	**N/A**	**From start**		**Max >30%**
Q23	Existance of a Proper Dispatch Office Underground with a Senior Official In-Charge (Shift-boss, MIC, Mine-Captain or Engineer)	No	Yes	Yes	No	No	No	**No**	**Yes**	**No (62%), Yes (38%)**	**No**
Q24	Existance of Computerized Equipment Dispatch System in place with Real-Time Monitoring Capabilities?	No	No	No	Yes	No	Yes	**No**	**Yes**	**No (62%), Yes (38%)**	**No**
Q25	When was an Equipment Dispatch System Installed?	None	20 years ago	None	1 year agc	None	10 yrs	**None**	**16 years**	**None(62%), Installed (**	**50% Installed**
Q26	Production Improvement in terms of Tons mined after installation of the Dispatch System	N/A	N/A	N/A	5%	N/A	> 30%	**N/A**	**From start**	**5% (17%), 30% (17%),**	**17.5% Impr**

Table 6.2 – Survey on decision support systems in mines

Some key findings from the table are:

- The results of the survey seem to indicate that quite a lot of mines in African context have not yet embarked on purposeful journeys to implement integrated system which supports real-time decision systems.
- This can be seen by the absence of important elements such as a dispatch system, absence of dispatch offices and mine operations control centers. Control centers are very key to the actualization of a real-time decision support system.

The next important element tested with the online survey was to check the current capabilities in underground mines in respect to real-time visibility and monitoring of operations. The following results gives a general overview on the findings. These responses show that for most of the mines, supervisors have no quicker ways of transferring instructions to their teams and working areas. This makes that the higher-level supervisors have very little ways of influencing outcomes as the mining processes goes on underground.



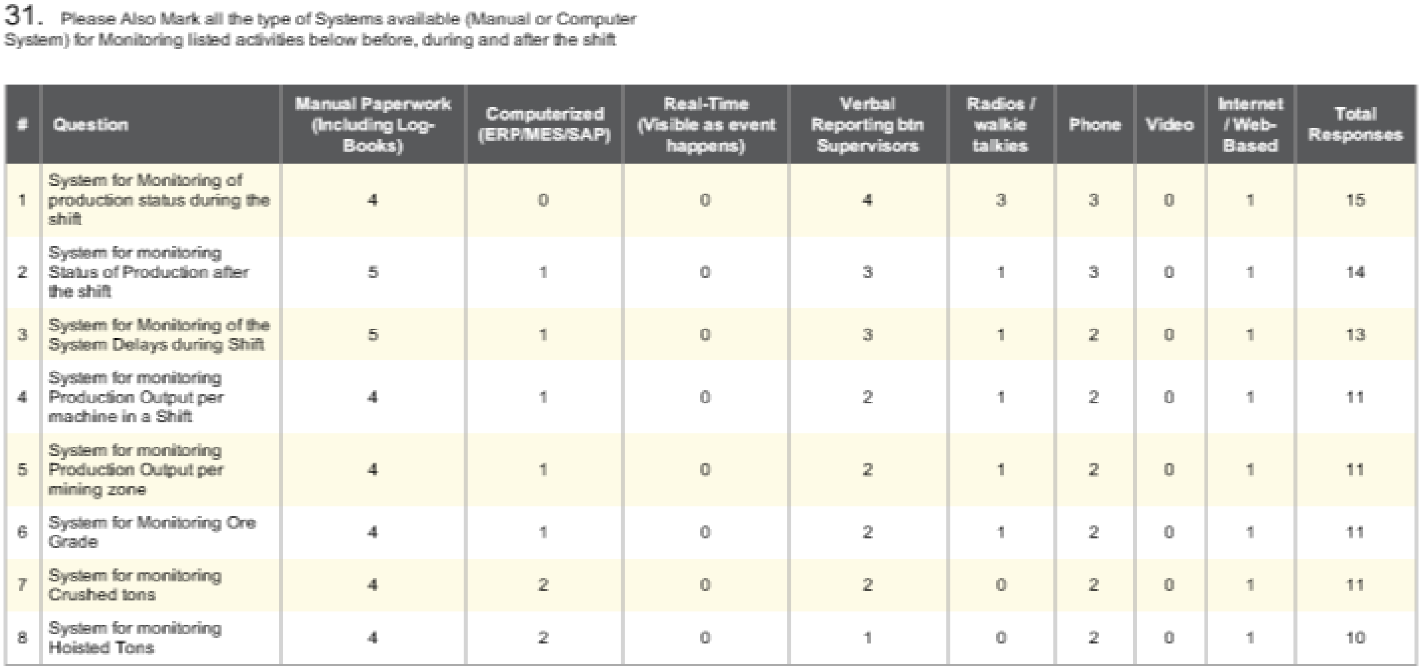
30. Please Mark all the type of Systems available (Manual or Computer System) for Supervisory Control of each of the listed activities below before, during and after the shift

#	Question	Manual Paperwork (Including Log-Books)	Computerized (ERP/MES/SAP)	Real-Time (Visible as event happens)	Verbal Reporting btn Supervisors	Radios / walkie talkies	Phone	Video	Internet / Web-Based	Total Responses
1	How do you know the Status of Equipment Start of Shift?	4	0	2	5	2	2	0	0	15
2	How do you know the Status of Working areas Start of Shift?	5	0	0	4	2	1	0	0	12
3	How do you know the number of Employees Start of Shift?	3	2	0	1	0	0	0	0	6
4	What is your System for Dispatch of Equipment?	5	0	0	3	1	1	0	0	10
5	How do you know the Status of Production after the shift?	4	1	0	2	0	2	0	1	10
6	Your system for Stoppages and Breakdown Reporting?	4	0	0	4	3	2	0	1	14

Table 6.3 – Survey of operating systems currently used in most mines

Only two responses said they have a real-time system to monitor the status of equipment start of shift, however none of the mines responded to have systems that can allow the supervisors to know the status of the working areas and employee as work progresses during the shift. Information in between and after shifts is transferred manually using paperwork or verbal means. Even the use of Radios/Walkie talkies is not used much. In a few cases it is used to report system stoppages and breakdowns.

Equally important is also availability of systems for process monitoring. None of the mines have Real-time systems for monitoring production status. All the processes are manual. System delays and production output monitoring is only known after end of shift through verbal and manual means.



31. Please Also Mark all the type of Systems available (Manual or Computer System) for Monitoring listed activities below before, during and after the shift

#	Question	Manual Paperwork (Including Log-Books)	Computerized (ERP/MES/SAP)	Real-Time (Visible as event happens)	Verbal Reporting btn Supervisors	Radios / walkie talkies	Phone	Video	Internet / Web-Based	Total Responses
1	System for Monitoring of production status during the shift	4	0	0	4	3	3	0	1	15
2	System for monitoring Status of Production after the shift	5	1	0	3	1	3	0	1	14
3	System for Monitoring of the System Delays during Shift	5	1	0	3	1	2	0	1	13
4	System for monitoring Production Output per machine in a Shift	4	1	0	2	1	2	0	1	11
5	System for monitoring Production Output per mining zone	4	1	0	2	1	2	0	1	11
6	System for Monitoring Ore Grade	4	1	0	2	1	2	0	1	11
7	System for monitoring Crushed tons	4	2	0	2	0	2	0	1	11
8	System for monitoring Hoisted Tons	4	2	0	1	0	2	0	1	10

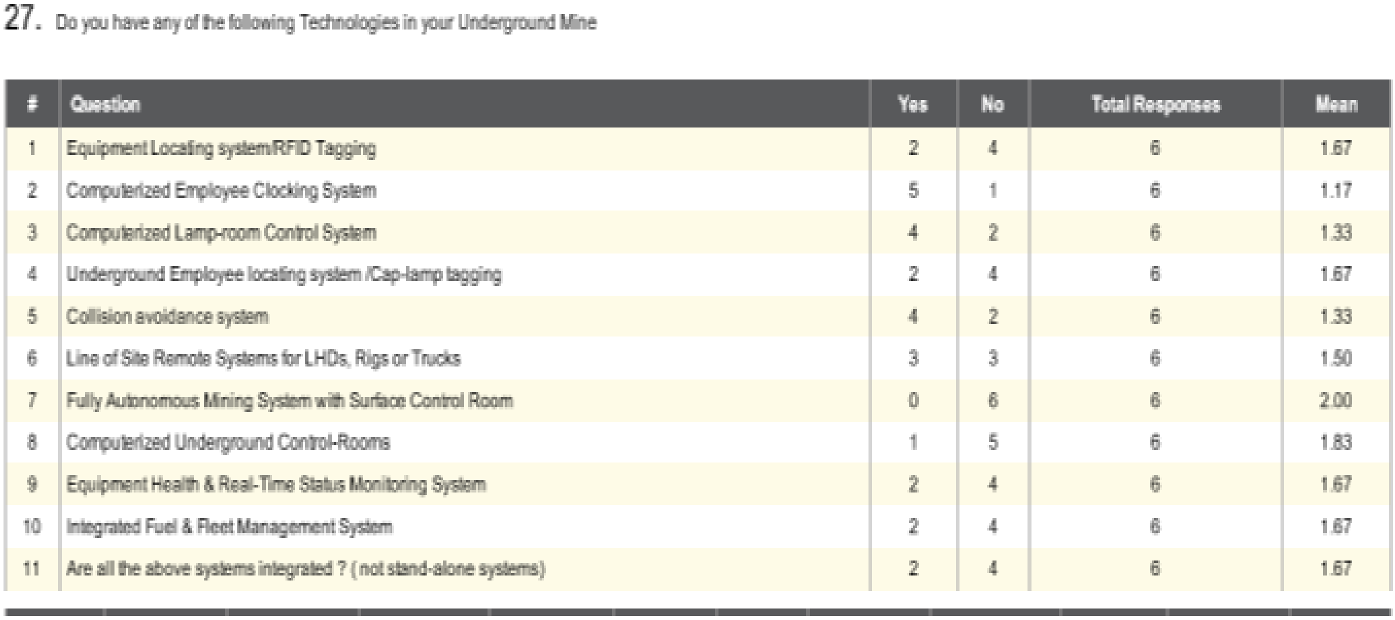
Table 6.4 – Survey of operations monitoring systems currently used in most mines

The above findings indicate the huge opportunities available in the mining industry to work on productivity improvements which can be realized through improved operational visibility.

6.3.3. Availability of enabling decision support technologies

The second most important area tested by the survey is to check the availability of technologies that enable implementing decision support systems underground. Tables 6.5, 6.6 and 6.7 below gives the general spread of decision support technologies in the African mining industry context.

The results indicated the opportunities that are available for organizations to adopt new technologies as 59% of the mines indicated that they do not have technologies which support real-time tracking and monitoring of people and equipment underground as indicated by Table 6.5 blow.



27. Do you have any of the following Technologies in your Underground Mine

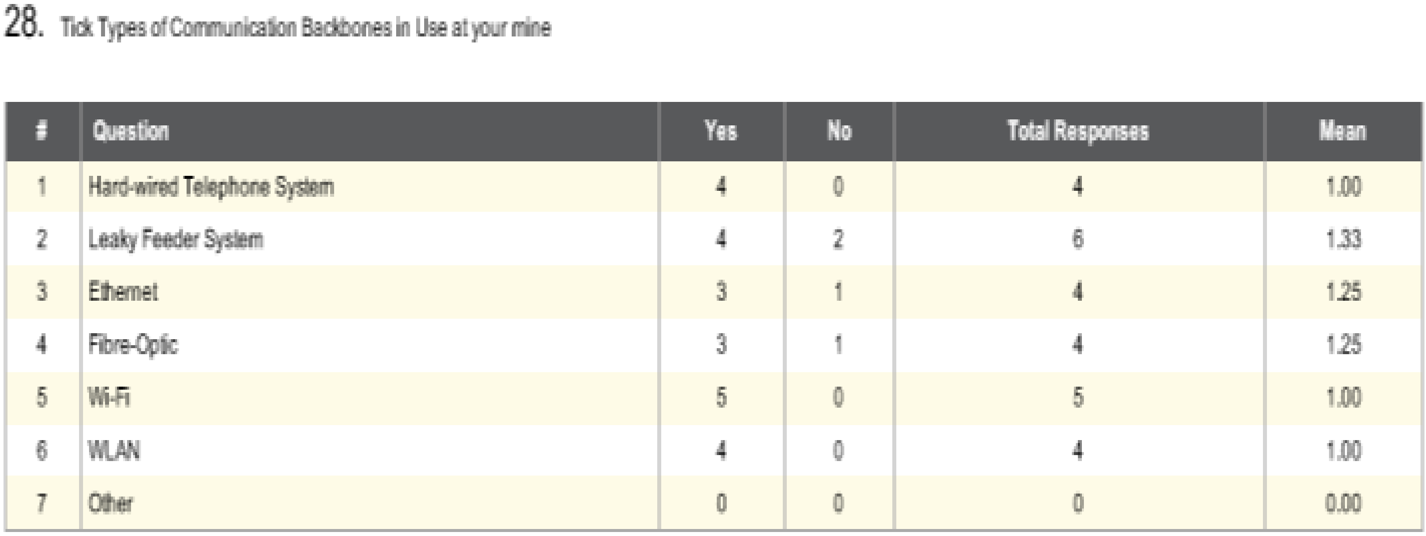
#	Question	Yes	No	Total Responses	Mean
1	Equipment Locating system/RFID Tagging	2	4	6	1.67
2	Computerized Employee Clocking System	5	1	6	1.17
3	Computerized Lamp-room Control System	4	2	6	1.33
4	Underground Employee locating system /Cap-lamp tagging	2	4	6	1.67
5	Collision avoidance system	4	2	6	1.33
6	Line of Site Remote Systems for LHDs, Rigs or Trucks	3	3	6	1.50
7	Fully Autonomous Mining System with Surface Control Room	0	6	6	2.00
8	Computerized Underground Control-Rooms	1	5	6	1.83
9	Equipment Health & Real-Time Status Monitoring System	2	4	6	1.67
10	Integrated Fuel & Fleet Management System	2	4	6	1.67
11	Are all the above systems integrated ? (not stand-alone systems)	2	4	6	1.67

Table 6.5 – distribution of technologies which support decision making systems

From the 66 responses, only 27 (41%) of the answers indicated positive to the availability of some technology for real-time monitoring system, 59% do not have such technologies. Such technologies include RFID tags for locating equipment and people underground, equipment health and status monitoring systems, lamp-room control systems, collision avoidance systems, integrated fuel management systems and underground control rooms. None of the mines have any fully autonomous systems.

The results of these findings show opportunity or improvements in the mines through implementation of real-time systems as most mines, at least in the Southern African region context, are yet to adopt and implement such systems.

Another very important enabler for implementing real-time systems in underground mining is the availability of a supporting communication infrastructure. From the mines surveyed, it is clear that most of the mines have now implemented communication backbones which have a capability to be upgraded for interfacing real-time systems. Communication links like leaky feeder and fibre optic systems have the capability of being upgraded to enable data, voice and video transmission.

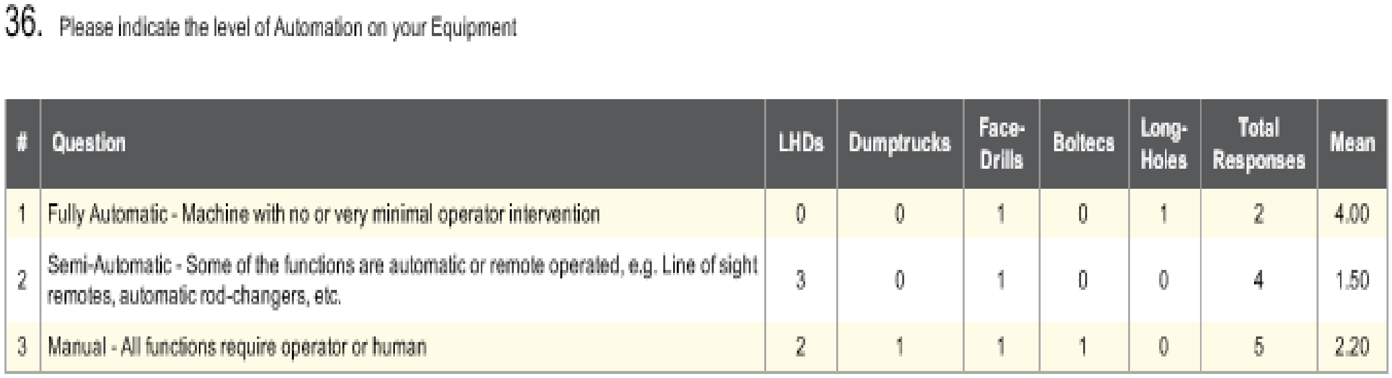


28. Tick Types of Communication Backbones in Use at your mine

#	Question	Yes	No	Total Responses	Mean
1	Hard-wired Telephone System	4	0	4	1.00
2	Leaky Feeder System	4	2	6	1.33
3	Ethernet	3	1	4	1.25
4	Fibre-Optic	3	1	4	1.25
5	Wi-Fi	5	0	5	1.00
6	WLAN	4	0	4	1.00
7	Other	0	0	0	0.00

Table 6.6 – Types of communications backbones in mines

In terms of the trackless mobile fleets, the common brands of equipment were found to be Atlas Copco, Sandvik and Caterpillar. Most of the responses 82% indicated that this equipment operates mostly in manual or semi-automatic modes. None of the 6 mines surveyed had a fully autonomous mining system. There is a bit of some automation, mostly on the LHDs which normally operate on line of sight remote systems, but that is as far as the automation goes.



36. Please indicate the level of Automation on your Equipment

#	Question	LHDs	Dumptrucks	Face-Drills	Boltecs	Long-Holes	Total Responses	Mean
1	Fully Automatic - Machine with no or very minimal operator intervention	0	0	1	0	1	2	4.00
2	Semi-Automatic - Some of the functions are automatic or remote operated, e.g. Line of sight remotes, automatic rod-changers, etc.	3	0	1	0	0	4	1.50
3	Manual - All functions require operator or human	2	1	1	1	0	5	2.20

Table 6.7 – Level of autonomous equipment in mines

6.4. A survey of a functional supervisory control system at Mine*PQR*

The general physical infrastructure for a functional real-time DSS was validated by an observational survey at *MinePQR* and will be discussed in this chapter. The communication system at MinePQR consisted of an Open Transport Network (OTN) backbone bases on the OSI protocol. A fibre medium was used to connect each OTN. The fibre running down the Shaft connected UG with surface. Leaky feeder was used for the radio communications and WiFi is used in the cave dispatch system. All this gets pulled through the OTN. The OTN had telephone cards that could be added for the telephones in each area.

MinePQR's production system used a block caving mining method displayed in Figure 6.9 below The DSS at the mine integrated the cave management system for managing the ore draw points, equipment control and dispatch, as well as management of the crews.

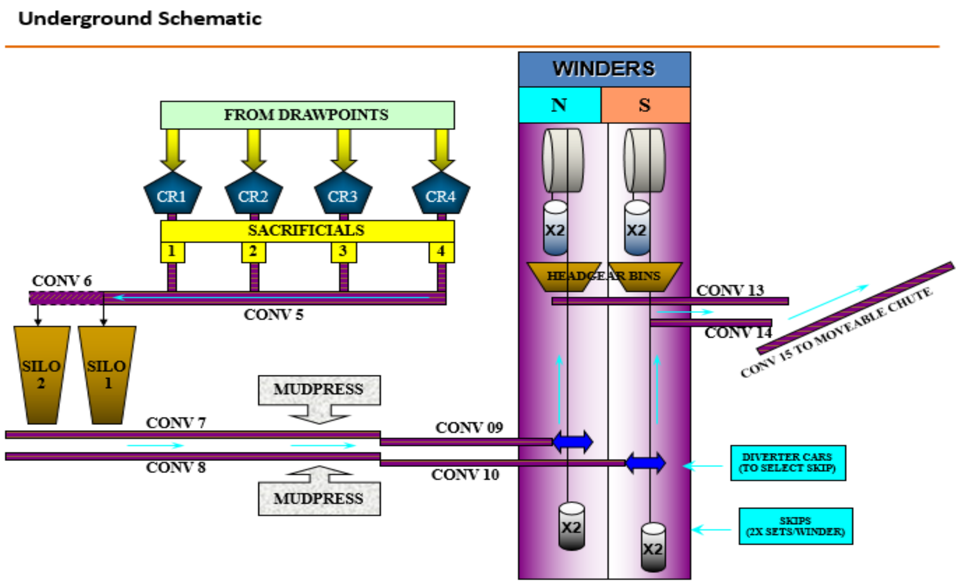


Figure 6.9 – Underground schematic for MinePQR

Ore from the draw points was loaded and hauled using Underground loaders with a 12.7-ton capacity bucket into four crusher grizzlies. The crusher grizzly acted as temporary storages with capacity of 500tons each.

The ore passed through the crushers after size reduction into a sacrificial conveyor system. From the conveyors the ore passed into two 2,700 ton each silo from where it was conveyed through a series of conveyors into ore skips. Ore was hoisted to the surface using 2 winders. The operations control system could monitor the whole value chain from ore generation to hoisting and conveyance to the surface milling plant with enough detail of control at each stage.

6.4.1. Supervisory control - how the operations control system at MinePQR operated?

The supervisory control system at the mine had three methods of capturing production data (buckets) for the loaders which were the key production equipment. These were:

- Automatic recording via RFID Tag detection and Wi-Fi communications at draw points and crusher ore tips
- Manual Arrival at loading locations via button presses (note here that these button presses may be generated either via the LHD Operator console or via the Dispatch utility. The latter used in the event of a communications failure).
- Manually adding the loads to the shift database after the fact. (end of shift)

The usual method used to capture the operations was through the RFID tags on the machines and the wireless network backbone. The LHD could detect RFID Tags placed at strategic locations throughout the cave. Depending on which tags the LHD detected, various actions were generated for the LHD.

For example, the LHD could arrive at a drawpoint, the on-board hardware detects the drawpoint tag and the LHD would be positively located at the drawpoint and a LOAD action generated. The LHD then travels to the assigned crusher, detects the crusher tag which completes the load/haul/dump cycle and the load recorded. The process would then be repeated. Loading at an incorrect drawpoint was flagged and could be reported on at the end of the shift.

Automatic capturing required that the on-board hardware, tags and communications were all working and, in the case of the RFID tags, correctly configured. In case of failure of the hardware, manual capturing of the information was permissible. If the RFID Tags or on-board Tag Reader hardware was not functioning the LHD operator could still manually arrive at locations however there was no way of monitoring the position of the LHD.

As there was still communication to the Operator console the LHD operator could still receive assignments to drawpoints and crushers. However as the on-board tag reader subsystem would not be working dispatch would assume that the LHD had loaded at the correct drawpoint. It would however not be possible to confirm the location of the LHD. The onus in this case would be on the LHD operator to press the ARRIVE button at drawpoints and/or crushers to record the load. In an underground scenario this was classified as a serious constraint due to the inability to visually monitor the LHD's

In the event of both the operator console and Tag Reader subsystem being non-functional the Dispatcher had the option to manually press buttons for the LHD operator using the DISPATCH utility. Actions performed via the dispatch utility were the same as if the LHD operator pressed the button.

A system was also in place to track personnel. A small RFID tag was installed in the cap lamps which would picked up by tag readers underground and reported back to the software. A SCADA system monitored the plant as seen on the Mine Operations Control Room shown in Figure 6.10

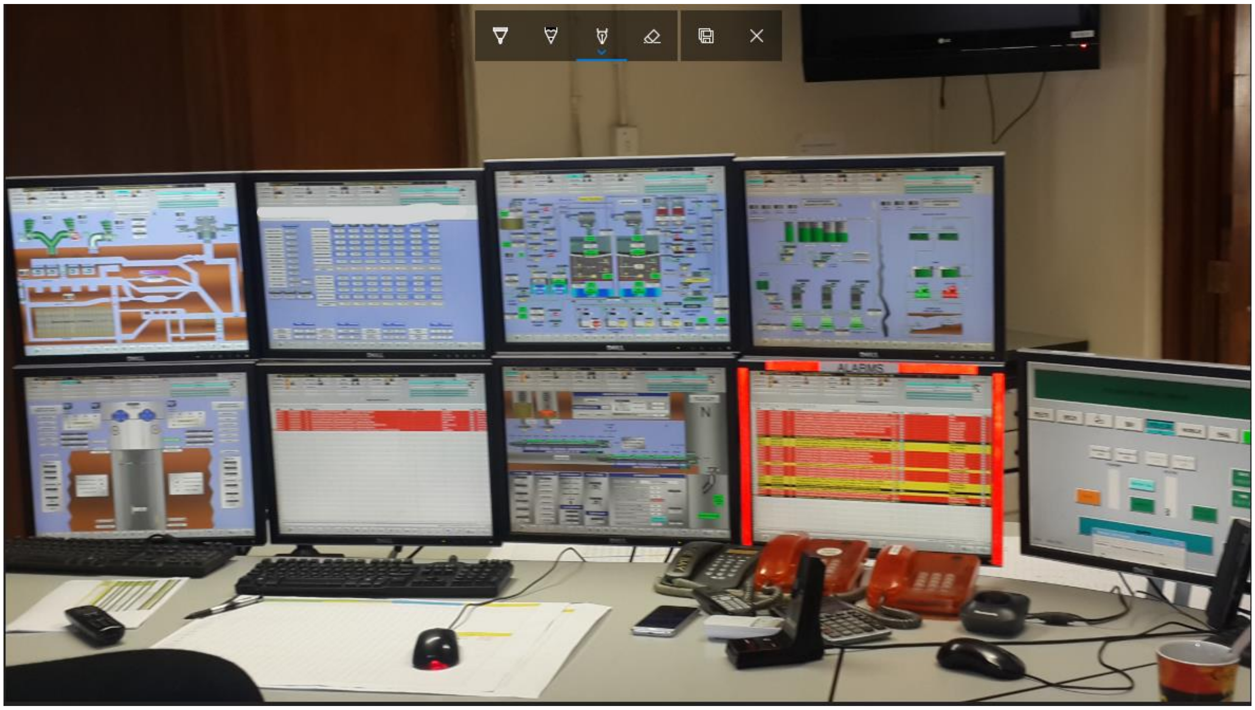


Figure 6.10 – Operations control centre for MinePQR

6.4.2. Mapping of the Decision Processes on an Underground mine DSS

During start of a Shift, there were certain key activities and information required for right decisions to be made that created maximum value for the shift. These decisions included: status of the cave and draw-points, status of equipment and personnel. Here it could be seen who has logged on to a LHD under the operator tab.

The first display was the geometric view of the cave which show the active mining areas and the status of the draw points as shown in Figure 6.11

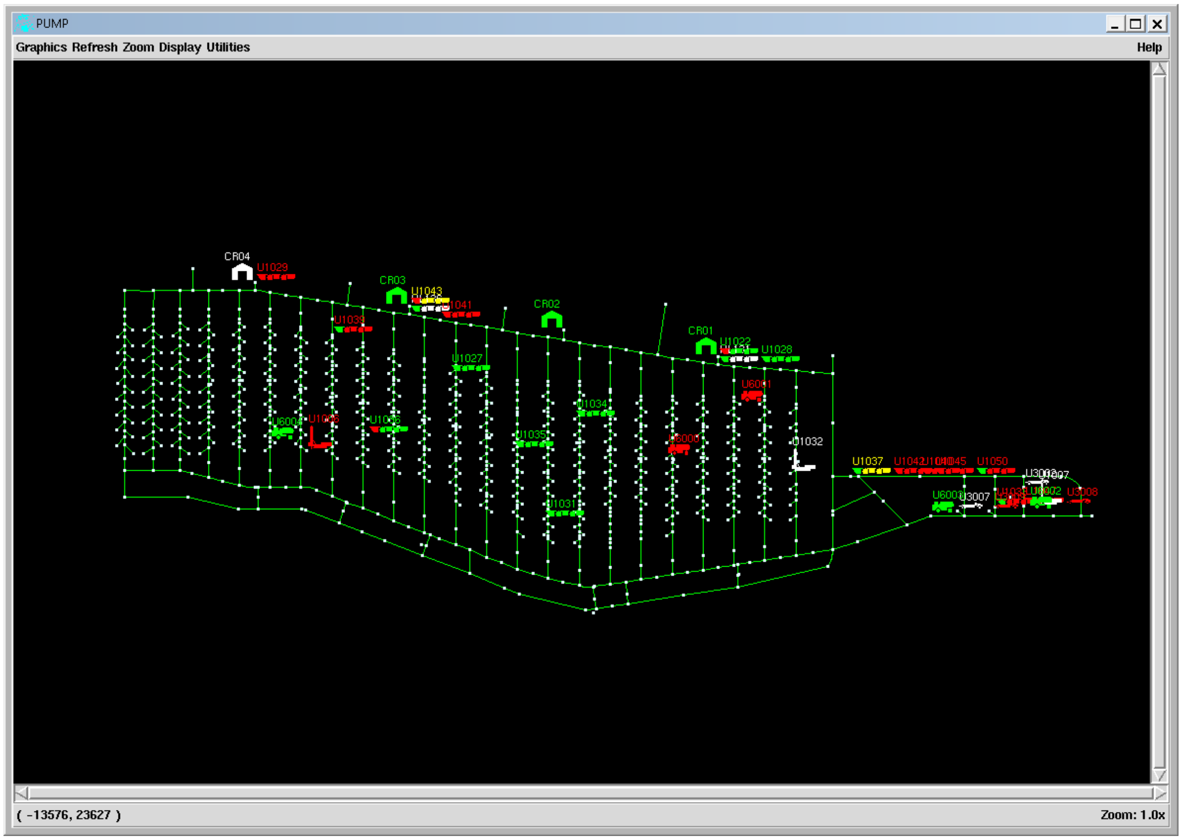
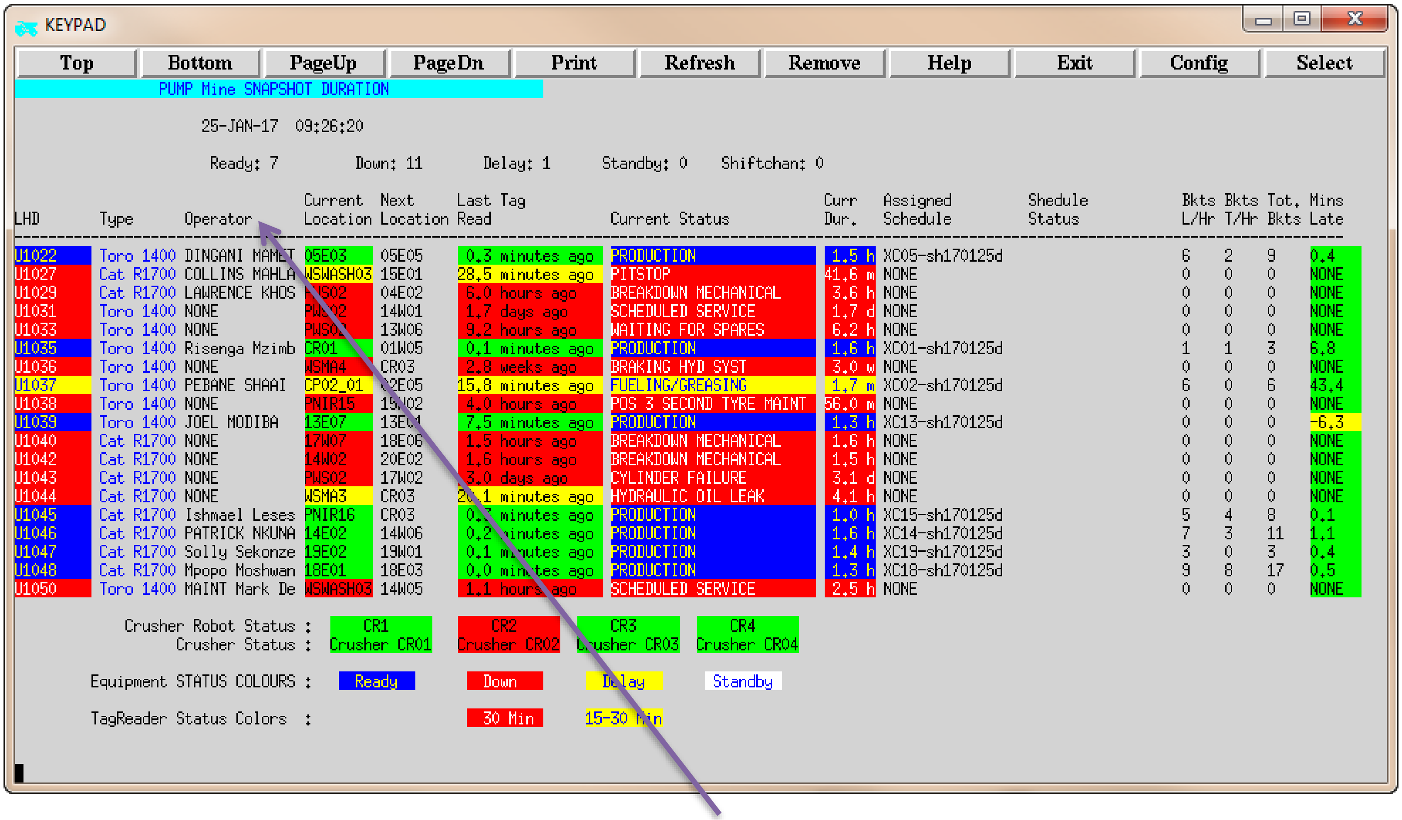


Figure 6.11 – Geometrical view of the cave at MinePQR

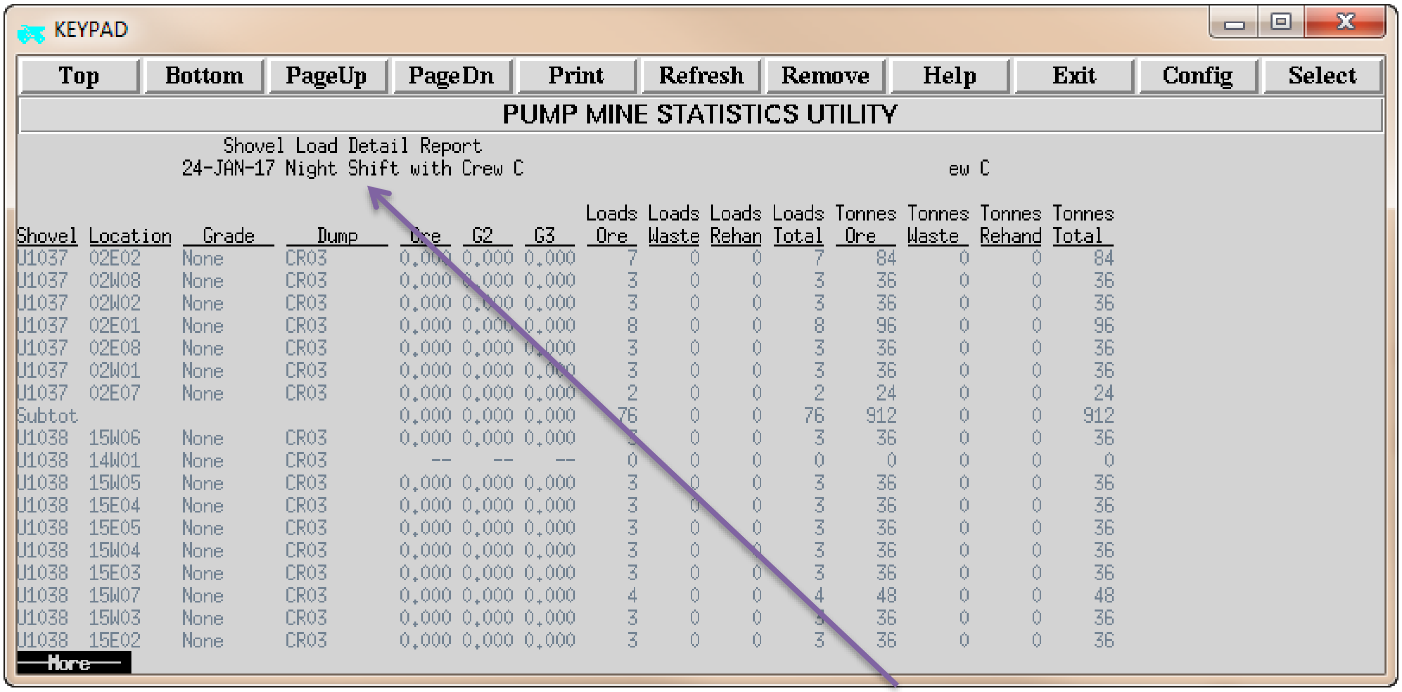
The next important point was to know the number of personnel or shift crew on the shift. The system did not have a clock in system on this mine but there was line up in the mornings and in this manner each supervisor knew how many people are on shift. The system could only determine who is logged on to a machine and on the software, side as displayed in Figure 6.12, 6.13 and 6.14



```
                          PUMP Mine SNAPSHOT DURATION

                          25-JAN-17  09:26:20

                           Ready: 7         Down: 11        Delay: 1        Standby: 0      Shiftchan: 0

                                    Current  Next     Last Tag                         Curr    Assigned           Shedule              Bkts Bkts Tot. Mins
LHD        Type       Operator      Location Location Read           Current Status    Dur.    Schedule           Status               L/Hr T/Hr Bkts Late
---------------------------------------------------------------------------------------------------------------------------------------------------------
U1022      Toro 1400  DINGANI MAMET 05E03    05E05     0.3 minutes ago PRODUCTION          1.5 h XC05-sh170125d                         6    2    9    0.4
U1027      Cat R1700  COLLINS MAHLA WSWASH03 15E01    28.5 minutes ago PITSTOP            41.6 m NONE                                   0    0    0    NONE
U1029      Cat R1700  LAWRENCE KHOS PWS02    04E02     6.0 hours ago   BREAKDOWN MECHANICAL  3.6 h NONE                                 0    0    0    NONE
U1031      Toro 1400  NONE          PWS02    14W01     1.7 days ago    SCHEDULED SERVICE     1.7 d NONE                                 0    0    0    NONE
U1033      Toro 1400  NONE          PWS02    13W06     9.2 hours ago   WAITING FOR SPARES    6.2 h NONE                                 0    0    0    NONE
U1035      Toro 1400  Risenga Mzimb CR01     01W05     0.1 minutes ago PRODUCTION          1.6 h XC01-sh170125d                         1    1    3    6.8
U1036      Toro 1400  NONE          WSMA4    CR03      2.8 weeks ago   BRAKING HYD SYST      3.0 w NONE                                 0    0    0    NONE
U1037      Toro 1400  PEBANE SHAAI  CP02_01  02E05    15.8 minutes ago FUELING/GREASING      1.7 m XC02-sh170125d                       6    0    6    43.4
U1038      Toro 1400  NONE          PNIR15   15W02     4.0 hours ago   POS 3 SECOND TYRE MAINT 56.0 m NONE                              0    0    0    NONE
U1039      Toro 1400  JOEL MODIBA   13E07    13E01     7.5 minutes ago PRODUCTION          1.3 h XC13-sh170125d                         0    0    0    -6.3
U1040      Cat R1700  NONE          17W07    18E06     1.5 hours ago   BREAKDOWN MECHANICAL  1.6 h NONE                                 0    0    0    NONE
U1042      Cat R1700  NONE          14W02    20E02     1.6 hours ago   BREAKDOWN MECHANICAL  1.5 h NONE                                 0    0    0    NONE
U1043      Cat R1700  NONE          PWS02    17W02     3.0 days ago    CYLINDER FAILURE      3.1 d NONE                                 0    0    0    NONE
U1044      Cat R1700  NONE          WSMA3    CR03     20.1 minutes ago HYDRAULIC OIL LEAK    4.1 h NONE                                 0    0    0    NONE
U1045      Cat R1700  Ishmael Leses PNIR16   CR03      0.3 minutes ago PRODUCTION          1.0 h XC15-sh170125d                         5    4    8    0.1
U1046      Cat R1700  PATRICK NKUNA 14E02    14W06     0.2 minutes ago PRODUCTION          1.6 h XC14-sh170125d                         7    3    11   1.1
U1047      Cat R1700  Solly Sekonze 19E02    19W01     0.1 minutes ago PRODUCTION          1.4 h XC19-sh170125d                         3    0    3    0.4
U1048      Cat R1700  Mpopo Moshwan 18E01    18E03     0.0 minutes ago PRODUCTION          1.3 h XC18-sh170125d                         9    8    17   0.5
U1050      Toro 1400  MAINT Mark De WSWASH03 14W05     1.1 hours ago   SCHEDULED SERVICE     2.5 h NONE                                 0    0    0    NONE

                  Crusher Robot Status :    CR1            CR2            CR3            CR4
                        Crusher Status :  Crusher CR01   Crusher CR02   Crusher CR03   Crusher CR04

            Equipment STATUS COLOURS :     Ready          Down           Delay          Standby

            TagReader Status Colors  :                    30 Min         15-30 Min
```

Here the system show who had logged on to a LHD under the operator tab.

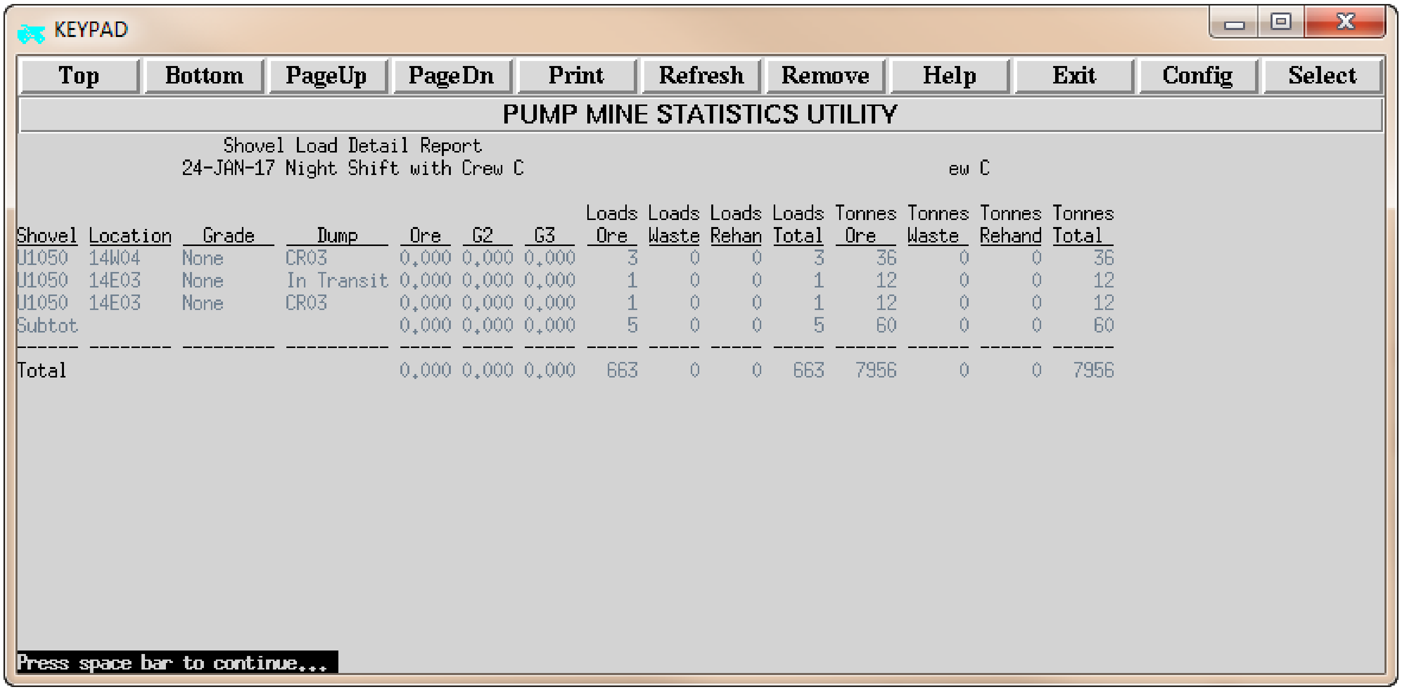
Figure 6.12 – Real-time status of trackless equipment during the shift



```
                 Shovel Load Detail Report
               24-JAN-17 Night Shift with Crew C                                   ew C

                                                                Loads Loads Loads Loads Tonnes Tonnes Tonnes Tonnes
Shovel Location   Grade       Dump      Ore    G2    G3     Ore  Waste Rehan Total  Ore   Waste  Rehand Total
U1037  02E02    None       CR03       0.000 0.000 0.000      7     0     0     7     84      0      0     84
U1037  02W08    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
U1037  02W02    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
U1037  02E01    None       CR03       0.000 0.000 0.000      8     0     0     8     96      0      0     96
U1037  02E08    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
U1037  02W01    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
U1037  02E07    None       CR03       0.000 0.000 0.000      2     0     0     2     24      0      0     24
Subtot                                0.000 0.000 0.000     76     0     0    76    912      0      0    912
U1038  15W06    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
U1038  14W01    None       CR03          --    --    --      0     0     0     0      0      0      0      0
U1038  15W05    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
U1038  15E04    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
U1038  15E05    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
U1038  15W04    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
U1038  15E03    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
U1038  15W07    None       CR03       0.000 0.000 0.000      4     0     0     4     48      0      0     48
U1038  15W03    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
U1038  15E02    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
--More--
```

Here we can see the individual performance of each LHD as per the shift selected

Fig 6.13 – Real-time status of each LHD performance during the shift



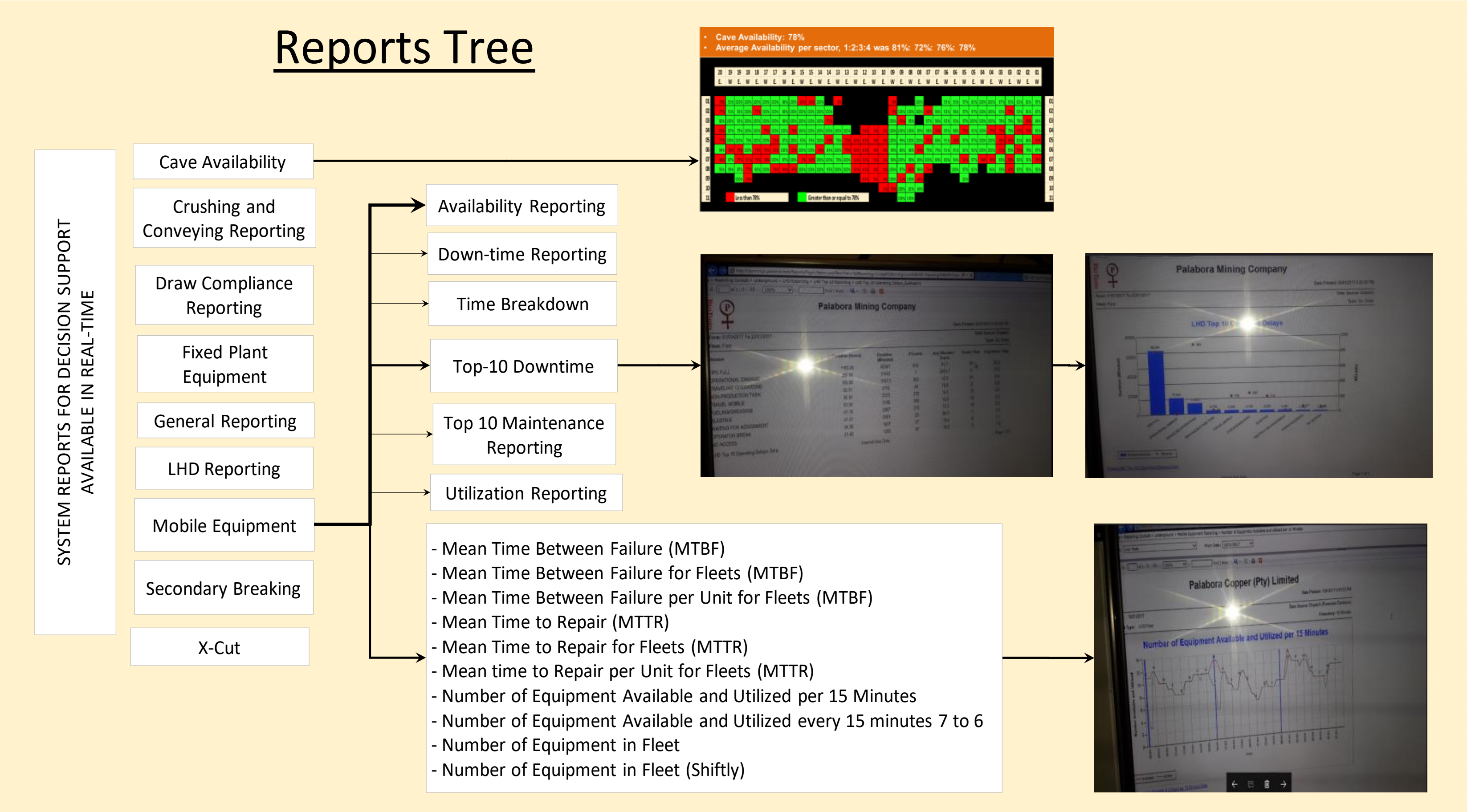
```
                 Shovel Load Detail Report
               24-JAN-17 Night Shift with Crew C                                   ew C

                                                                Loads Loads Loads Loads Tonnes Tonnes Tonnes Tonnes
Shovel Location   Grade       Dump      Ore    G2    G3     Ore  Waste Rehan Total  Ore   Waste  Rehand Total
U1050  14W04    None       CR03       0.000 0.000 0.000      3     0     0     3     36      0      0     36
U1050  14E03    None       In Transit 0.000 0.000 0.000      1     0     0     1     12      0      0     12
U1050  14E03    None       CR03       0.000 0.000 0.000      1     0     0     1     12      0      0     12
Subtot                                0.000 0.000 0.000      5     0     0     5     60      0      0     60
------ -------- --------- ---------- ----- ----- ----- ----- ----- ----- ----- ------ ------ ------ ------
Total                                 0.000 0.000 0.000    663     0     0   663   7956      0      0   7956







Press space bar to continue...
```

Here we can see the shift report for the tons loaded and hauled to the crushers. This is not the actual hoisted values.

Figure 6.14 – Real-time status of tons loaded to the crusher

6.4.3. Reports to support better decision making

The dispatch system creates a total of about ___ real-time reports which aid in faster decision making. Below is a report tree of the system.



Reports Tree

SYSTEM REPORTS FOR DECISION SUPPORT AVAILABLE IN REAL-TIME

- Cave Availability
- Crushing and Conveying Reporting
- Draw Compliance Reporting
- Fixed Plant Equipment
- General Reporting
- LHD Reporting
- Mobile Equipment
- Secondary Breaking
- X-Cut

- Availability Reporting
- Down-time Reporting
- Time Breakdown
- Top-10 Downtime
- Top 10 Maintenance Reporting
- Utilization Reporting

- Mean Time Between Failure (MTBF)
- Mean Time Between Failure for Fleets (MTBF)
- Mean Time Between Failure per Unit for Fleets (MTBF)
- Mean Time to Repair (MTTR)
- Mean Time to Repair for Fleets (MTTR)
- Mean time to Repair per Unit for Fleets (MTTR)
- Number of Equipment Available and Utilized per 15 Minutes
- Number of Equipment Available and Utilized every 15 minutes 7 to 6
- Number of Equipment in Fleet
- Number of Equipment in Fleet (Shiftly)

- Cave Availability: 78%
- Average Availability per sector, 1:2:3:4 was 81%: 72%: 76%: 78%

Figure 6.15 – Real-time equipment status reporting

6.5. CHAPTER CONCLUSION

This chapter looked at the technology and hardware aspects of real-time decision support. This was illustrated through taking a look at how a communication infrastructure can be configured in a mining set-up, with real time capabilities in mind. The use of MAP and ISO protocols for open architecture were discussed.

The chapter proceeded to give results of an on-line survey which was conducted to check the level of technologies in some mines in Africa. The results of the survey illustrated that there are still opportunities available in terms of applying new technologies in Africa. A survey of 10 mines show that only 50% of the mines say they have a control room of some sort which is used to monitor operations underground. However those that have a proper equipment dispatch office with computerized systems were only 38%, leaving 62% without a proper dispatch system. Also 59% do not have technologies for tracking and monitoring activities underground. Such technologies include RFID tags for locating equipment and people underground, equipment health and status monitoring systems, lamp-room control systems, collision avoidance systems, integrated fuel management systems and underground control rooms. None of the mines surveyed had any fully autonomous systems.

The chapter concluded by discussing the technology used in a mine which was operating an active computerized dispatch system. The discussion showed how a good dispatch system is used to monitor production of LHDs in stopes and updating of production status in real time. The system is also used to monitor status of draw points on a continuous basis, as well as equipment health so that breakdowns are noted and reported immediately.

It can thus be concluded that technologies and systems are now available to implement real-time monitoring systems even in underground operations to improve productivity and decision making for management.

7. DISCUSSION AND INTERPRETATION OF RESULTS

7.1. CHAPTER OVERVIEW

The overall objective of the study was to identify improvement opportunities and potential benefits which can be obtained in an underground trackless mine through criteria that support better decision making. This was to be achieved through application of detailed production analysis techniques for an operating underground mine.

The three sub-objectives to be addressed in the research were:

(1) To analyse key technical factors that impact mining production rates in a trackless production system – Chapter 4.

(2) To identify major operational activities which maximize effective operating times for improved visibility and better decision support systems – Chapter 5.

(3) To illustrate how a DSS architecture can be configured for improved decision support – Chapter 6.

This chapter discusses how these objectives were met. Section 7.2 discusses the generic framework adopted in analyzing some of the important decision factors which impact on mine outputs. Section 7.3 discusses a method for developing a real-time decision framework for a trackless operation for quick operational decision making. Section 7.3 summarizes some of the physical configurations of a real-time decision support system. Each potential improvement will be noted by an Improvement Number.

7.2. FRAMEWORK - DECISION FACTORS FOR IMPROVED PRODUCION RATES.

7.2.1. Level_0 – Defining system context and framework for analysis

Figure 7.1 is an illustration of the method employed in this study to analyse the important technical decisions which can unlock value in a trackless mine. The framework is based on implementing analysis techniques for serial and parallel production systems. The first step was to set the boundaries of the production system to be analyzed. In a trackless system it is best to take the battery limits from the insitu rock up to the ROM pad. In this case the production system can be modelled as an interconnected serial/parallel production system with various work stations interconnected by buffers in between Figure 7.2.

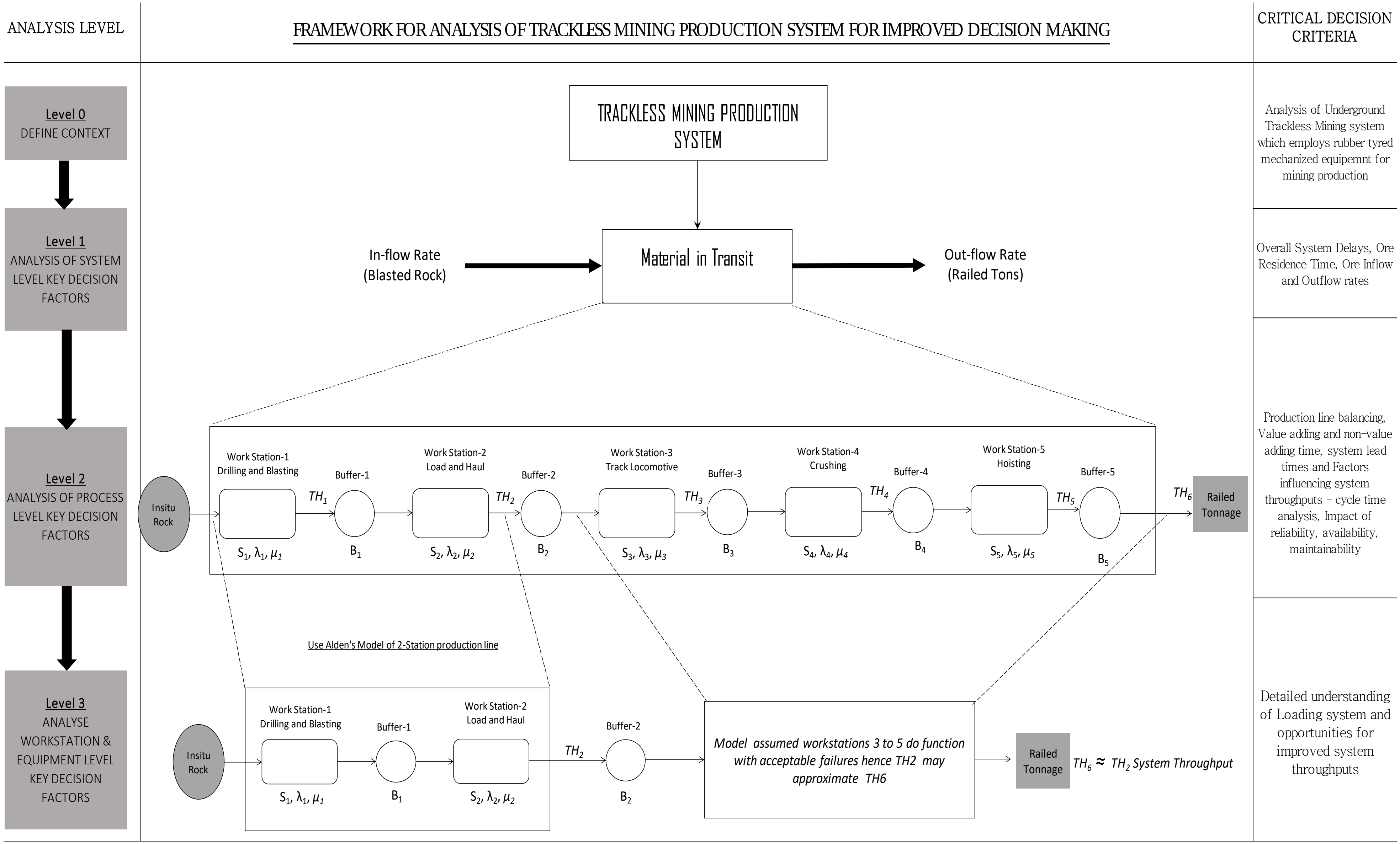


Figure 7.1 – Framework for production system analysis

The production system was modelled into five work stations, namely the drill and blast work stations, load and haul work stations, tramming work stations, conveyance and crushing work stations, and hoisting work stations to the ROM pad.

In a parallel system, a work station consists of several machines of similar type. Thus, drill and blast work stations may have a certain number of drill rigs distributed in the mine, load and haul may consist of a set of loader and truck arrangements or only loaders, locomotive tramming may or may not exist in some mines, etc.

MineABC operated a total fleet of 145 underground Mobile Diesel Equipment (MDE)/ trackless equipment across its four shafts which included load haul dumpers (LHDs) /scooptrams, underground low-profile dump trucks, drill rigs, roof support bolters, and various utility vehicles and trucks. The mining processes depend directly on the effective operation of the MDE for drilling and blasting, loading and hauling of ore, roof support as well as transporting of personnel and materials/consumables in and around the mines. The spread of the equipment across the shafts was as below:

Distribution of Mobile Diesel Fleet at MineABC

	LHDs	Dump-Trucks	Drill Rigs & Bolters	Utility Vehicles	Land-Cruisers	**Total Fleet**
Shaft A1 (Conventional Mine)	7	3	0	4	3	**17**
Shaft A2	9	14	2	4	3	**32**
Shaft A3	16	13	9	12	8	**58**
Shaft A4	7	9	8	8	5	**37**
Grand Total	**39**	**39**	**19**	**28**	**19**	**144**

Table 7.1 – MineABC Fleet summary

Of the total LHDs, 23 were used for direct production. In order carry to out a full analysis on the system, the system was aggregated into an equivalent serial system. Figure 7.2 shows how the existing production system was arranged as serial and parallel system for analysis.

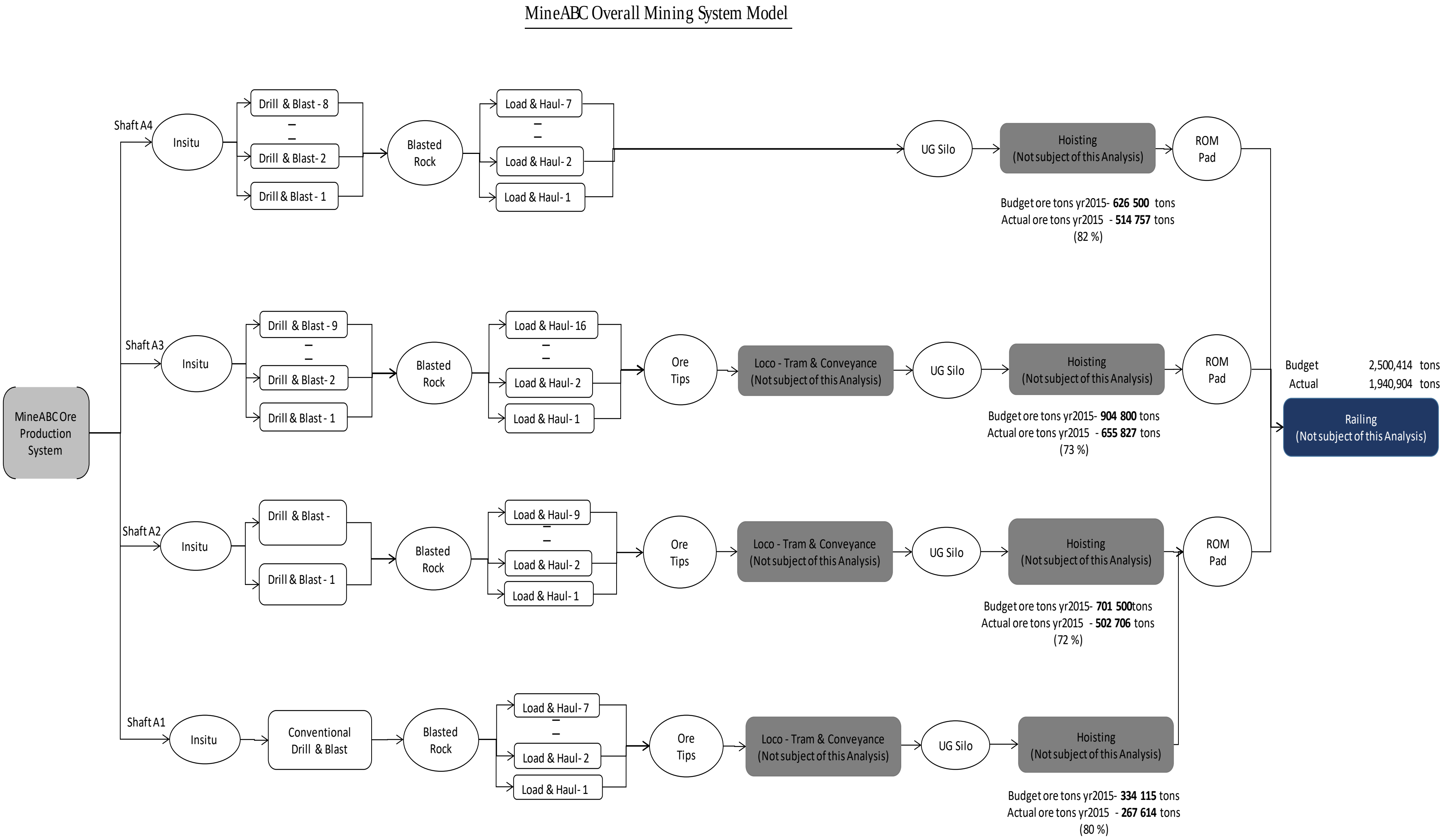


Figure 7.2 – Overall production system model for MineABC

For analysis purposes, an equivalent serial system for analysis of the various shafts systems was then modeled from Figure 7.2 and aggregated to be represented by Figure 7.3 showing the key technical parameters which are important in analysis as defined earlier in Section 3.5.3

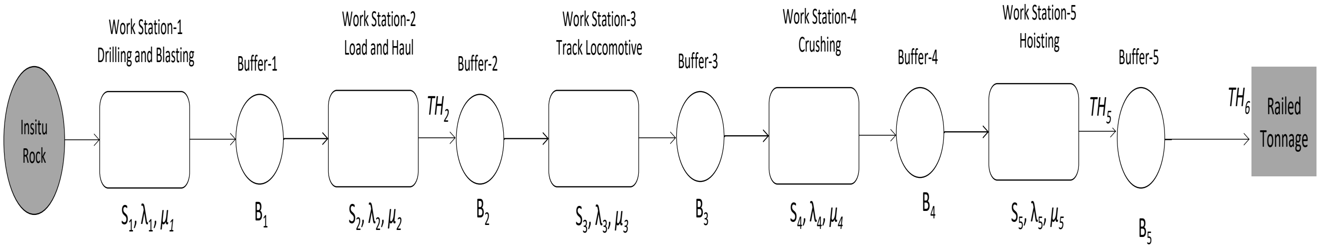


Figure 7.3 – Equivalent trackless mine production system for analysis

The approach in carrying out analysis of the production system was to define the system boundaries and understand the context of what needs to be achieved. Thereafter to analyse the system level decisions which impact system throughputs, followed by work station decisions.

7.2.2. Value drivers - margin and profit equation

Based on profit equation (4.10), Table 7.2, Figure 7.4 is showing an idealized profit versus hoisted tonnage profiles at different price scenarios for MineABC.

Notes	Hoisted Tons per Month	*MineABC Mining Operating Profit at various price scenarios*			
		2015 Prices	1.5 x 2015 Prices	2 x 2015 Prices	3 x 2015 Prices
	50,000	(216,875)	(206,563)	(195,750)	(184,938)
	70,000	(107,801)	(79,112)	(49,442)	(19,772)
	90,000	(38,943)	22,495	85,554	148,613
	110,000	(1,997)	110,715	225,846	340,978
	130,000	11,341	198,002	388,042	578,083
	150,000	9,375	296,813	588,750	880,688
2015 Average tons	161,742	4,427	365,198	731,201	1,097,204
Breakeven tons at 2015 Prices	218,000	22	886,677	1,782,837	2,678,997
Budget tons (5-year Ave)	227,528	10,845	1,019,366	2,038,240	3,057,115
Maximum possible tons, based on the available Hoisting Capacity	318,413	529,889	3,302,090	6,094,568	8,887,047

Note: - 2015 average weighted metal price used (Copper & Nickel) was US$6810/ton of metal sold

Table 7.2 – Table of operating profit vs hoisted tons at various prices

Results from the Figure 7.4 and table 7.2 can be used as decision charts to determine on a continuous basis the business profit as tonnage and price profiles changes. Figure 7.4 is a tool which could be used for decision making as prices of the commodity varies to below and above the 2015 prices. The Figure also show that if prices dropped below 75% of 2015 prices, the business would not make any profit at available plant capacity.

Table 7.2 shows that at the prevailing prices in 2015, the average operating tons were 161,742 tons per month, the breakeven tons were 218,000 tons, the 5-year average budget tons were 227,528 tons, and maximum possible tons to be produced from the mine based on the available hoisting capacity of 14,696 tons/day and 260 operating days in a year was 318,413 tons. This scenario shows that there was a possibility of operating the mine to capacity if tonnage could be operated above the budget.

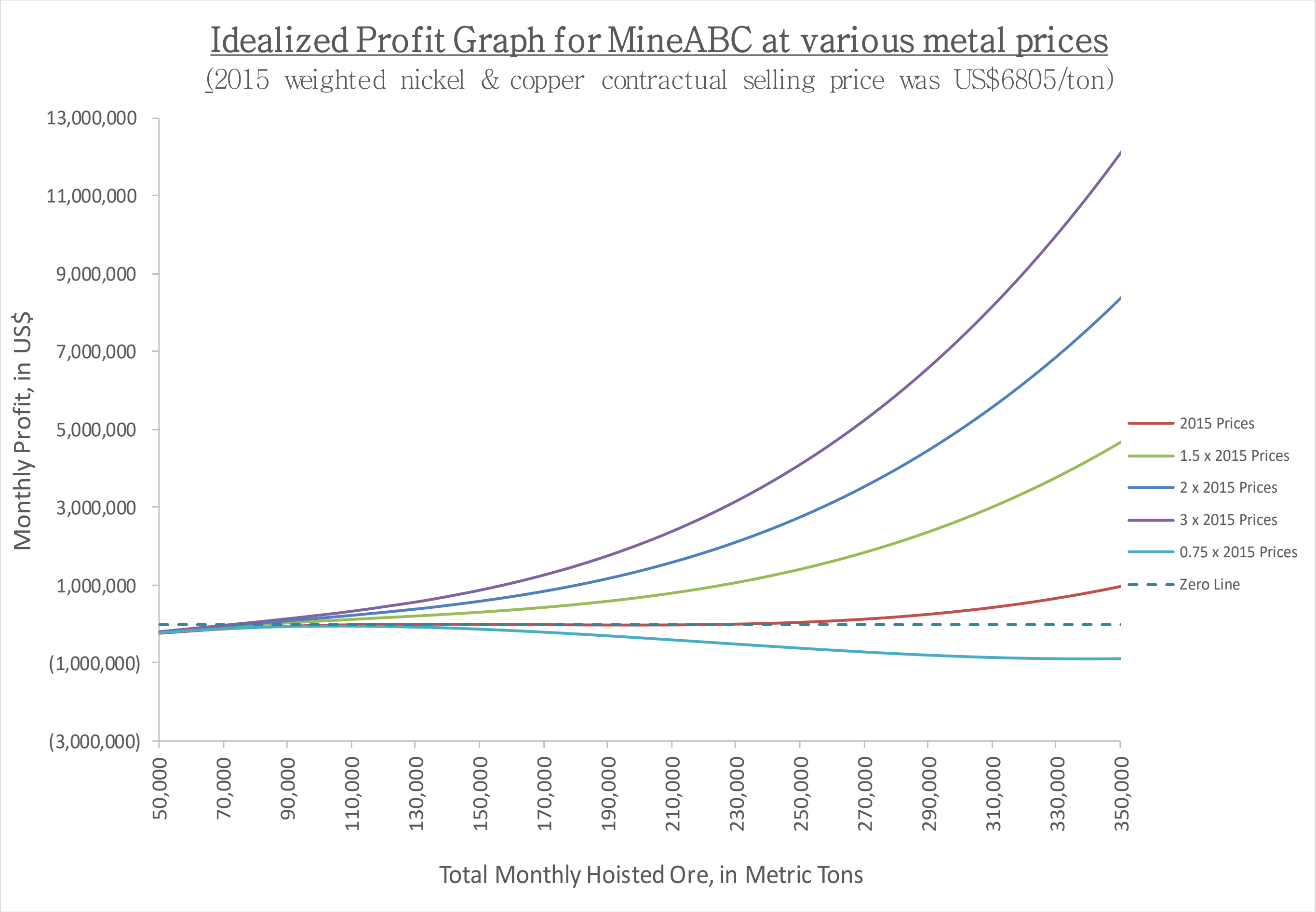


Figure 7.4 – Operating profit vs hoisted tons at various prices

7.2.3. Level_1- System level - decisions on ore residence/delay time (system lead time)

The main decision criterion at system level is to use production information to analyse the inflow and outflow statistics of a production system and identify the lags in output versus input. Production at MineABC clearly showed that the outflow measured as railed tons lagged the inflow tons which are the drilled and blasted tons as illustrated in Figure 7.5.

The difference between inflows and outflows is the work in process or stock of the production line. The fact that the outflow is less than the inflows show accumulation of the ore underground which could have been hoisted out to make money for the business.

The analysis of material in transit allowed the analysis of the overall delays of the production system. This was based on recognizing that the outflow of a dynamic system is a function of the material in transit and the average residence time of the material in the system as defined by Sterman (2000). The average residence time can be defined as the overall system lead time. Figure 7.6 is a model used for this analysis of ore residence time in the system.

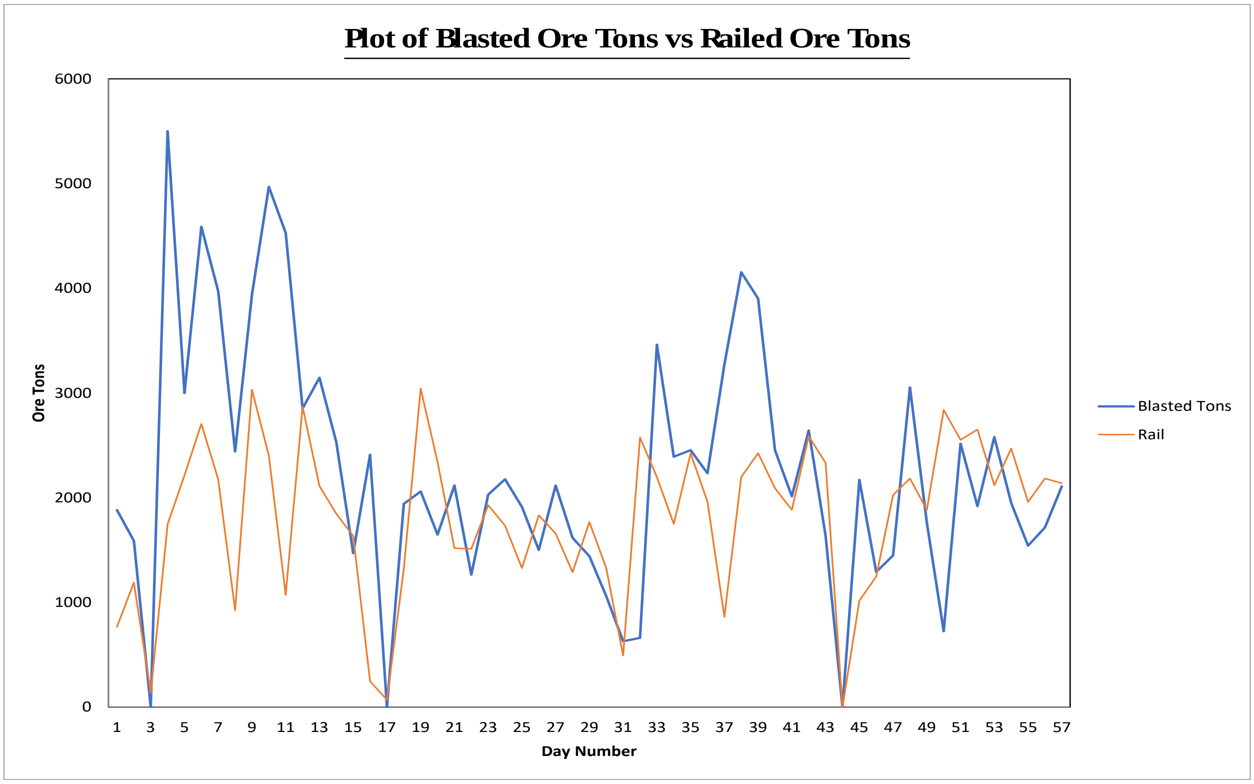


Figure 7.5 – Variation of production inflow (blasted tons) vs production outflow (railed tons)

For a trackless process, the residence time of the ore will be the time the material will take from blast up to the ROM pad stockpile. According to Sterman (2000), the derivative of stock in transit is basically the difference between the inflow stock minus the outflow as discussed in section 2.2 and equation (2.2). Figure 7.6 illustrates the structure of material(ore) in transit.

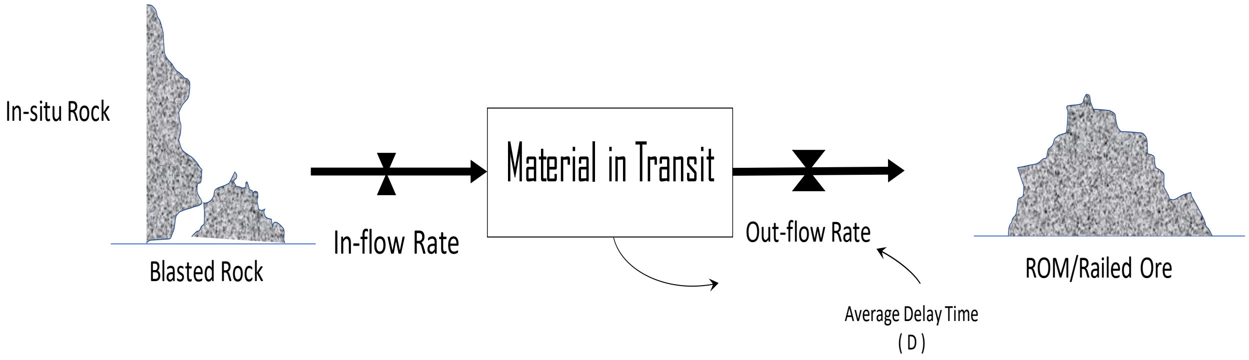


Figure 7.6 – Overall model of material in transit in a mine

Based on the historical information at MineABC, plot of inflow minus the outflow gave the equation of stock or material in transit equation (4.7) using 58 days data that was available:

$$\text{Outflow}(t) = \text{Material in Transit}, S(t)/\text{Delay time}(D)$$

$$\text{Outflow}(t) = (518.3[t - t.\ln(t)] + 2053t)/D \qquad (4.7)$$

Using equation 4.7, the delay times were across the battery limits from the insitu rock to the railed tons at ROM pad. The results are illustrated in Figure 7.7 which show the flow and stock dynamics of the serial production system with different system delay times.

The results in Figure 7.7 give opportunities of improvements if ore in transit residence times can be reduced. The main improvement in volumes of ore comes from the fact that as the residence time of the ore in the system is reduced, it gives capacity to blast and move more tons of ore in production.

For example, since it took 7.95 days for a ton of ore to migrate the system, less ore will be moved per time compared to if the residence time is reduced and more capacity is created to blast more ore tons and to move more if the down-stream processes allow.

Average Ore Residence Time (Days)	Ore Tonnage Outflow (Railed)
2	10592
4	5296
5.13	4129
6	3531
7.95	2665
8	2648
10	2118
12	1765
14	1513
16	1324
18	1177
20	1059

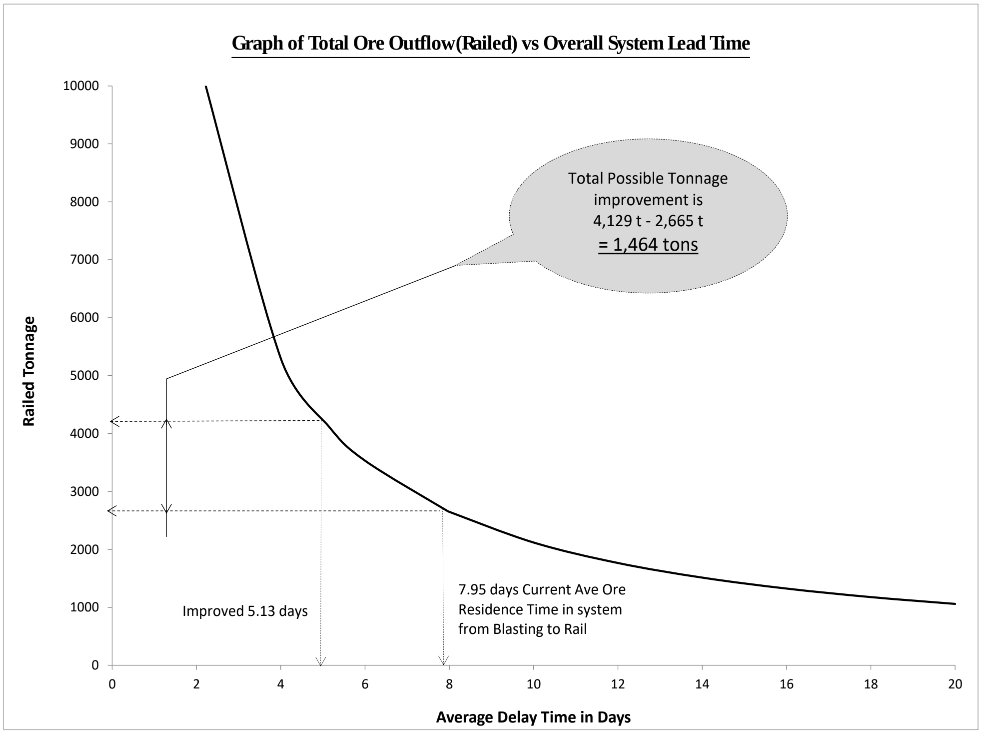


Figure 7.7 – Simulated variation of railed tons vs ore-residence time at MineABC

Deductions from Figure 7.7 highlight the possibility of increasing the railed tons through reduction in ore-residence time in the system. This could practically be achieved through reductions in drill and blast delays, load & haul delays and hoisting delays which affect the overall ore residence times as shown in table 7.2. An increase of about 1464 tons/day (55% of current tonnage) in railed tonnage was a possibility in this case (see Figure 7.7).

Ore in Transit Analysis for 2015 at MineABC

Stage	Flow from	To	Average Daily Ore Tons in Transit	Averge Daily Ore Tons Outflow from stage	**AS-IS** Ore-Residence Time between the stages (Days) (= Ore in Transit/Outflow)	**After Improvement** Ore-Residence Time between the stages (Days) (= Ore in Transit/Outflow)	NOTES
1	Drill & Blast	Load & Haul	2416	2101	1.24	0.33	Reduce delay to 1-shift
2	Load and Haul	Tramming	2362	2047	1.14	0.33	Reduce delay to 1-shift
3	Tramming	Hoisting	2119	1839	1.87	1.87	
4	Hoisting	Railing	1843	1803	3.70	2.59	Reduce delay by 30%
		Total			7.95	5.13	

Table 7.3 – Improved ore in transit residence times

This would be equivalent to extra annual tonnage of 374,784 tons only for Shaft A3 for a 256-day production year (256 days x 1464 tons/day), which is 41 % increase in tonnage (374,784/904,800).

Improvement -1: **Improvement through reductions in ore residence times in the system and Overall system lead time. Assuming the same percentage increase of 41% across the four shafts from the existing production of 1,940,904 will give an equivalent of - 803,956 extra ore tons/year or 66,996 tons/month for the whole mine**

7.2.4. Level_2 - Process level decisions – reducing gross cycle times to level production

Level 2 analysis of the production system looked at the process level to identify the gross cycle times at each of the critical work stations in relation to the Takt time at each station. This is described in section 4.4 of the report. Equation (4.9) is the equation which is used to calculate the gross cycle time and Figure 7.6 Is a schematic representation of the various cycle time losses and how they make up the gross time:

$$CT_{gross} = CT_{net} + CT_{co} + CT_{up} + CT_{Q} \tag{4.9}$$

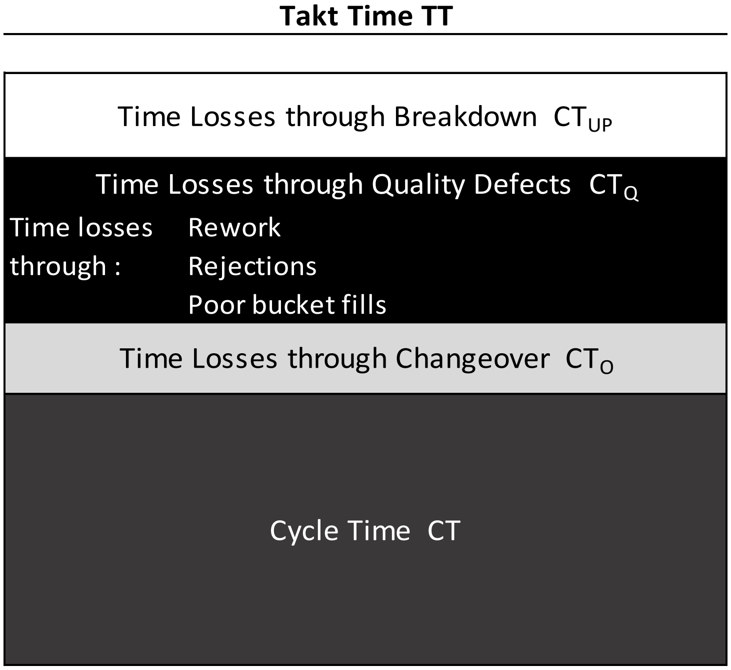


Figure 7.8 – Schematic of time losses in production (changeover, uptime restrictions and quality)

The gross cycle time in this case represents number of minutes taken to produce a ton of ore. Takt time is the maximum cycle time required to meet the daily target. If the gross cycle time is greater than the Takt time, then the respective work station is constrained. However, if the gross cycle time is less than the Takt time, then there is extra capacity.

As shown in section 4.4, an analysis of the different mining processes work stations was done to identify the gross cycle time for each process using operational data for year 2015 at MineABC ShaftA3. The resulted is summarized in Table 4.8. The various gross cycle times were then plotted to give the load balance chart for the mine illustrated Figure 7.8.

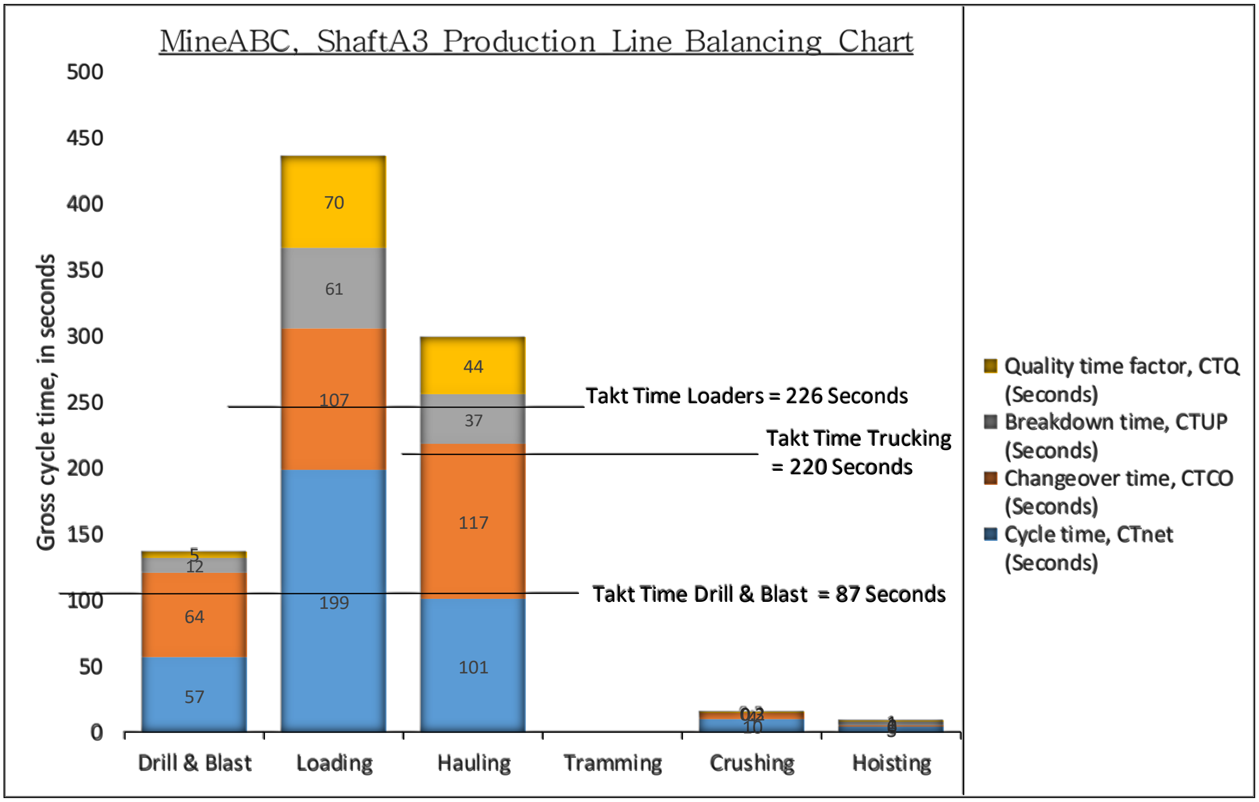


Figure 7.9 – Figure of gross cycle time (changeover, uptime restrictions and quality)

Figure 7.9 illustrates that the drill and blast, loading and truck hauling processes are constrained as their gross cycle times are above their Takt times, whereas the crushing and the hoisting processes show that they have excess capacity. Therefore, the key areas which needed consideration were the drill and blast work stations, the loading work stations, and the truck haul work stations. Some deductions that could be drawn from this were that:

- The gross cycle time at the drill and blast stations were mostly affected by the large change-over times and the net cycle time to drill a face. Changeover times include the time to move drill rig from one face to another and these impact on the ability to generate ore quickly
- Figure 7.9 also show that the major process bottlenecks for the mine was due to the LHDs. The gross cycle time for loaders of 437 seconds to move a ton of ore was 93% above the required Takt time of 226 seconds. The actual capacity of the mine was thus seriously constrained by the loaders performance as this cycle time was far large than the time required to meet the production target.
- Dumptrucks were also constrained due to large changeover times and net cycle time.

If the LHDs gross cycle time is reduced from 437 seconds to the required Takt time of 226 seconds, the 211 seconds gained on each loader would mean an increase in tonnage moved from an average of 8.24 tons moved per hour (= 3600/437) to 15.9 tons/hour (=3600/226) per loader.

The largest opportunity to reduce gross cycle time lay in reducing the net cycle time, CT_{net}. The net cycle CT_{net} time is the ideal cycle time that is based on the equipment capability as discussed in section 7.2.5.2. One way of reducing CT_{net} is to reduce the total distance travelled by the loaders during the loading operations.

Taking an example of the CAT R1600G loader that was being used in ShaftA4, the CT_{net} can be calculated using the Rim-pull charts found in the Caterpillar Performance Handbook. Using the Rim-Pull Figure for a CAT R1600G loader (Appendix D1), the maximum speed of a loaded LHD at total resistance of 12% (10% gradient +2 % Rolling), will be maximum 9.6 km/hr.

If the net cycle time CT_{net} is 199 seconds (Table 5.8/Figure 7.3), and taking 60% time to be the time the LHD takes loaded tramming, one-way distance is calculated as:

Approximate distance of travel one way = time x speed
= (60% *x* 199sec/3600) *x* 9.6 km/hr. = 318 metres

This shows that the loaders are tramming an average distance of 318 metres loaded. If the maximum tramming distance for the loaders is reduced to a maximum of 200 metres, then there is opportunity to improve the loader cycle time by as much as 59% if the loader's loaded tramming distance is kept at maximum of 200 metres.

Now assuming the gross cycle time of 437 seconds can be reduced to at least the Takt time of 226 seconds, then there could be a net increase of 7.66 tons/h extra tons moved by the loaders from 8.24 loads/h to 15.9 tons/h per loader. Therefore, for a loader operating effectively only 32% of a 24-hour day (7.68hrs), this will give a total of 346,384 extra tons for 23 operating loaders.

Improvement-2: **346,384 extra tons possible by reducing the gross cycle time of the loaders from 437 seconds per ton of ore to the Takt time 226 seconds per ton of ore giving an additional 7.6 tons/hr per loader**

7.2.5. Level_3 – Work station and equipment level technical decisions

7.2.5.1. Throughput equation for various failure rates (λ)and repair rates (μ)

The decisions critical at work station level revolves around the reliability, maintainability and availability capacity of each production equipment. Analysis was done for the 23 LHDs used in production to develop the relationships which can guide better decision making. The LHDs were chosen for analysis in this case as they had biggest capacity constraint as illustrated by Figure 7.8.

The equation which determines the throughput rate (TH_2 *in loads/h)* at various work stations was calculated and shown to be represented by equation (4.10) which show the variation with the availability index given by, the formula (μ/(λ+μ).

$$TH_2 \text{ (loads/h)} = S\left(\frac{\mu}{\mu+2\lambda}\right).\left(\frac{2+(\lambda+\mu)/\mu)(B\mu/S)+(\lambda/\mu)(B\mu/S)}{2+((\mu+\lambda)/\mu)(B\mu/S)}\right) \qquad (4.10)$$

The availability index is a function of the machine reliability represented by the failure rate of the plant or work station λ (=1/MTBF) and the repair rate represented by μ (= 1/MTTR). Variations of the throughput rate with λ, μ and (μ/(λ+μ) show various opportunities as is discussed in the following sections *7.2.5.2*, *7.2.5.3* and *7.2.5.4.*

7.2.5.2. Improvement in Loader cycle time at fixed Availability Index

The variation of loader cycle time presented opportunities to increase plant throughput at the same performance rate of the equipment. This is illustrated in the steps below:

(1) A plot of TH_2 vs ($\mu/(\lambda+\mu)$) gave an "as-is" situation which was represented by equation (4.11) and Figure 4.18.

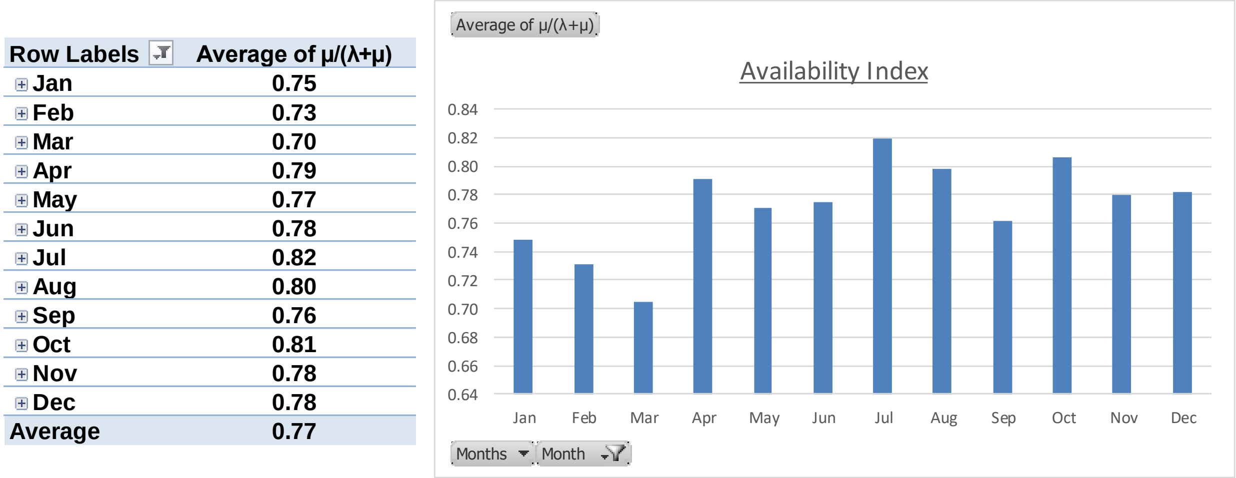
$$TH_2 = 3.5577(x)^{0.1476} \tag{4.11}$$

(2) A plot of an improved situation was done and was represented by equation (4.16) and Figure 4.20,

$$\boldsymbol{TH_2 = 7.535(x)^{0.6049}}, \quad \textbf{whereby } (x) \textbf{ is the availability index } (\mu/(\lambda+\mu)) \tag{4.16}$$

(3) Figure 4.20 from equation (4.16) is assuming that practical interventions were possible to be made to increase the throughput for each LHD at the same availability indexes from below 3.2 load/h which was being achieved by each LHD to above 5 loads/hr. Plotting the new equation showed practical benefits that could be realized through shifting the graph Figure 4.18 upwards.

(4) The availability index for the mine was an average 0.77 (77%) for the year and showed a steady variation throughout the year as shown by Figure 7.10



Row Labels	Average of μ/(λ+μ)
⊞ Jan	0.75
⊞ Feb	0.73
⊞ Mar	0.70
⊞ Apr	0.79
⊞ May	0.77
⊞ Jun	0.78
⊞ Jul	0.82
⊞ Aug	0.80
⊞ Sep	0.76
⊞ Oct	0.81
⊞ Nov	0.78
⊞ Dec	0.78
Average	**0.77**

Figure 7.10 – Availability Index for MineABC 2018

Figure 7.11 shows the distribution of the mine's average LHD cycle times in 2015.

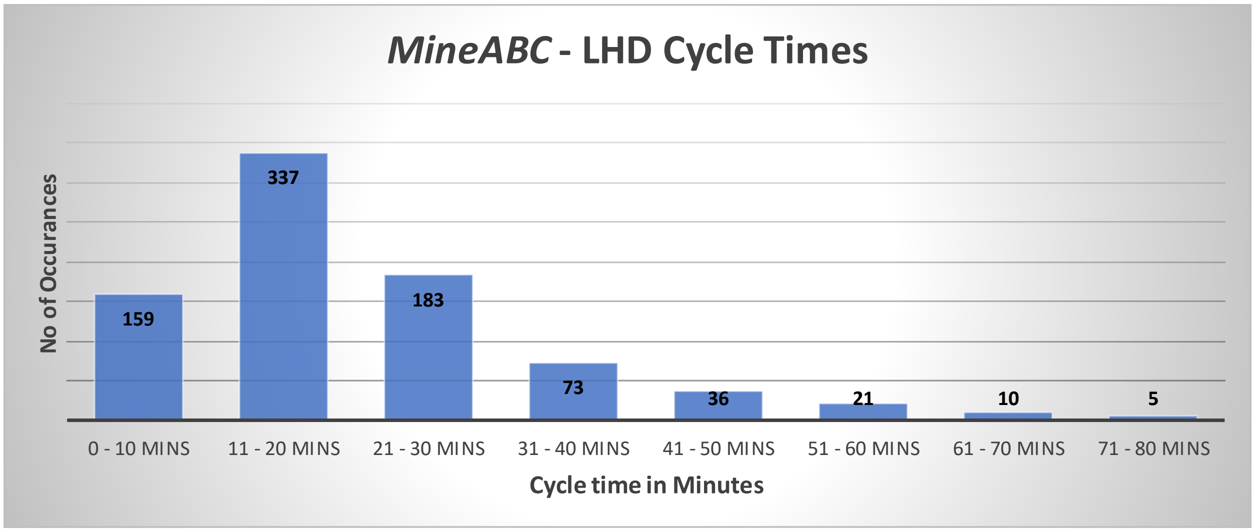


Figure 7.11 – MineABC mean loaders cycle time distribution in 2015

(5) Figure 7.11 shows that 60% of the loader cycle time is below 20 minutes and 40% is above 20 minutes. If the median of the cycle time is pushed to 15minutes (0.23hrs), at $\mu/(\lambda+\mu) = 0.77$, the throughput rates can be increased from 4.5 loads/hr. to 6.5 loads/hr.

(6) Based on the equation (4.16), $\mathbf{y = 7.535x^{0.6049}}$ the throughput rate of the loaders at 0.77 index could be improved from around 3.4 loads/hr to 6.5 loads/hr per loader.

(7) For 23 production loaders at throughput rate of 3.2 loads/hr, an average bucket factor of 6.5 tons/bucket and 46% utilized hours for 30.5 days per month, this is equivalent 161,742 tons/month or 1,940,904 tons/year.

(8) For an improved throughput rate of 6.5 loads/hr per loader, this is equivalent to 309,318 tons/month (Table 4.7) which is 147,581 extra tons representing or 91% increase. On an annual basis this will be close to **3,711,816,** which is extra tons of **1,770,972** unlocked in the system. This is only through ensuring that no loader operates at a production rate below 5 loads/hr. Based on researcher experience, practical potential rate would be to average at least 10 loads/hr per each loader.

$\mu/(\lambda+\mu)$	Throughput1 ($TH_1 = 3.5577x^{0.1476}$) Loads/hr/LHD	Total Tonnage 1 (for 23 LHDs)		Throughput2 ($TH_2 = 7.535x^{0.6049}$) Loads/Hr/LHD	Potential Tonnage 2 (for 23 LHDs)	Increament Tonnage
0.1	2.53	118,990.41		1.87	87,927.74	(31,063)
0.2	2.81	131,808.67		2.85	133,726.95	1,918.28
0.3	2.98	139,937.80		3.64	170,897.82	30,960.02
0.4	3.11	146,007.78		4.33	203,381.75	57,373.96
0.5	3.21	150,896.76		4.95	232,773.13	81,876.36
0.6	3.30	155,012.63		5.53	259,913.94	104,901.32
0.7	3.38	158,580.00		6.07	285,315.71	126,735.71
0.8	3.44	161,736.50		6.58	309,317.88	147,581.38
0.9	3.50	164,572.83		7.07	332,159.88	167,587.05
1.0	3.56	167,152.14		7.54	354,018.44	186,866.30

Table 7.4 – Throughput vs Availability Index at improved loads/h for MineABC

Figure 7.12 illustrates potential tonnage increments per month at the various availability levels of the loaders through cycle time reductions

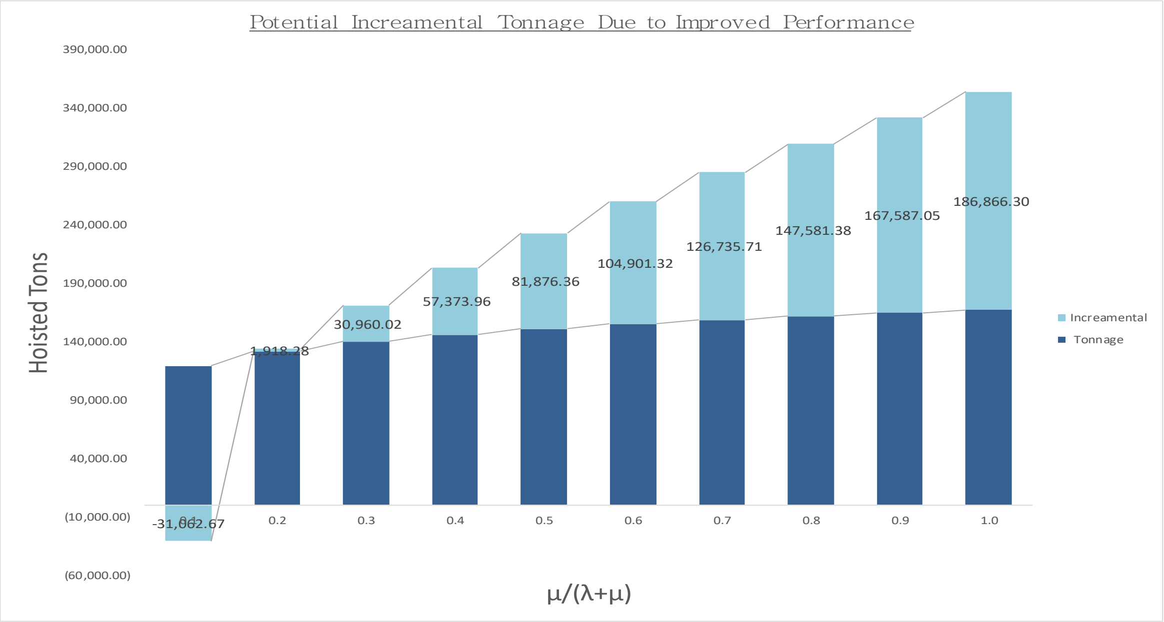


Figure 7.12 – Incremental Throughput vs Availability Index at improved loads/hr for MineABC

<u>Improvement-3</u>: **Due to improvement in loader cycle time, a new production rate of 309,318 tons/month at 0.8 availability index (Table 7.4 and Figure 7.5) can be achieved. This represents additional tonnage of 147,581 tons per month (91% increase), equivalent 1,770,972 tons/year extra.**

7.2.5.3. Improvement in Reliability – reduction of failure rates at fixed cycle times

As illustrated in section 4.5.2.3, an important tactic would be to improve the reliability of the plant by reduction in failure rates at fixed cycle times. Figure 4.22 is an important decision chart which can be used for that improvement. If cycle time reduction is achieved to below 15 minutes (0.25 h), then various throughputs improvements can be realized depending on the reduction in failure rate, λ.

Figure 7.13 illustrates the use of Figure 4.22 to gain tonnage improvements. This is based on the equation (4.13) and (4.15) described in section 4.5.2.2 and presented below.

$$TH = \mathrm{K_c}.\left(\frac{1}{CT}\right) \tag{4.13}$$

$$\text{Where, } \mathrm{K_c} = \left(\frac{\mu}{\mu+2\lambda}\right).\left(\frac{2+2\lambda+\mu)}{2+\mu+\lambda}\right) \tag{4.15}$$

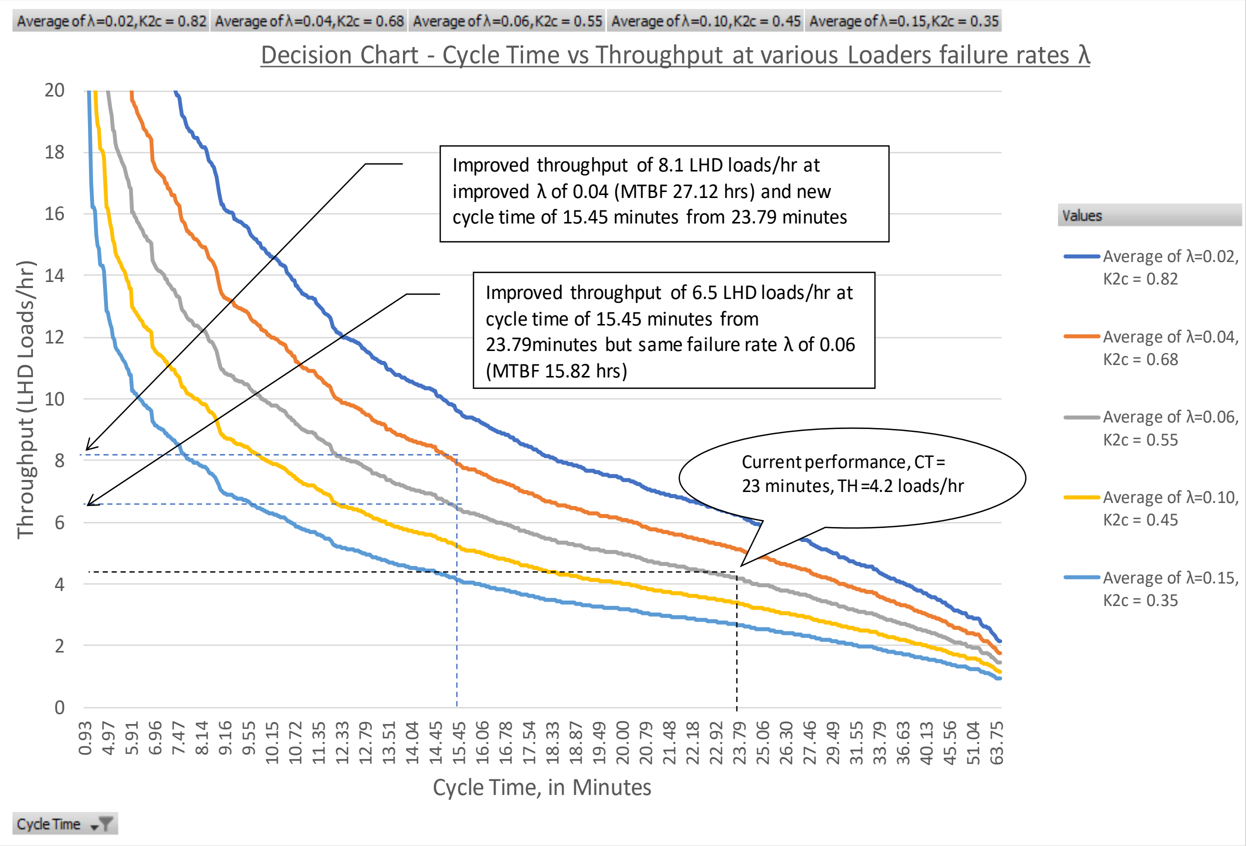


Figure 7.13 – Decision chart for improved plant reliability (reduced failure rate λ)

(9) Therefore, for a fleet of 23 production loaders at throughput rate of 8.1 loads/h, an average bucket factor of 6.5 tons/bucket and 32% LHD daily utilized hours for 26 days per month (200 hrs./month), this is equivalent to **241,802** tons/month or **2,901,630** tons/year.

(10) This is an improvement of **80,060** tons per month over and above the improvement from reduced cycle times. Annual improvement will be **960,720** tons.

<u>Improvement-4</u>: Improvement in reliability through MTBF and reduction in failure rate giving extra 80,060 tons/month and annually 906,720 tons. New production rate is 241,802 tons/month and annually 2,901,630 tons.

7.2.5.4. Reliability decision chart – Failure rate vs cost

As an aid to improved reliability decision making, an analysis of the cost versus the plant reliability was done and illustrated in Figure 7.14. Figure 7.14 is a very important decision chart which can be used to make economic and productivity decisions for the equipment.

Due to the ages of the machines, most of the loaders at MineABC were being pushed to the 3rd and 4th quadrant of the decision chart.

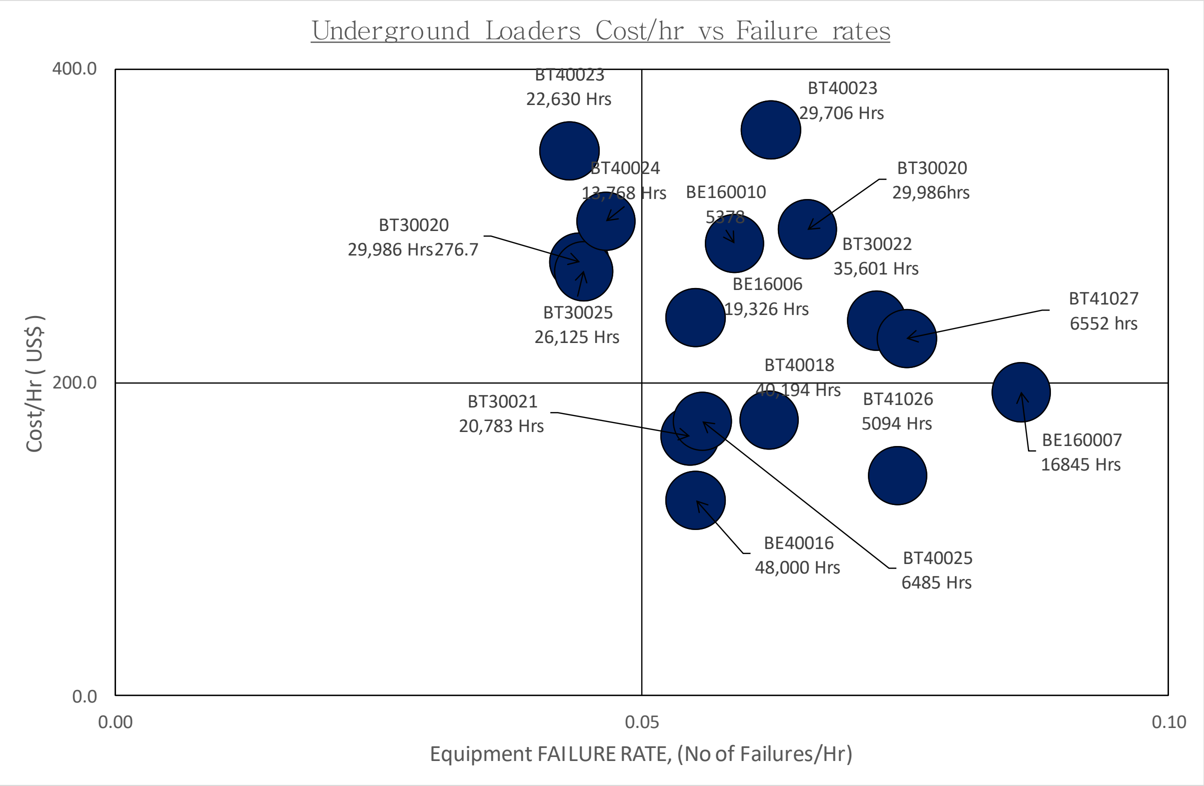


Figure 7.14 – Loaders (LHDs) decision table

Important business decisions could be made and deduced from Figure 7.14:

- The behavior of the machines is being pushed to high failure rate and high cost as the usage age increases.
- Some low hour machines are having high failure rates though at lower costs. This is reasonable during running in periods of new machines where they are expected to have high failure rates and is also consistent with the bath-tub curve in Figure 4.23. Here the failure rate is very high at beginning and then bottoming up at mid-life of around 22,222hrs.
- The high costs on the new machines would be expected to decrease after run-in.
- However, the big concern is on the machines with high lifetime hours and high failure rate machines. These should not be expected to be coming down as the machines were now beyond reasonable operating hours. What should have been expected would be a continual increase in costs at very high failure rates, which impact process reliability and throughput.

7.2.5.5. Improvement in Maintainability – reduced MTTR at various cycle times

The third important factor for improvement is the reduction in mean time to repair (MTTR) which is represented by the repair rate μ in the equation (4.10). Decision chart Figure 7.15 is used to determine the impact of variation in repair rate λ on throughput, assuming the failure rate and cycle times are kept constant. This graph is a development from Figure 4.27 and equation (4.16) and (4.17) in Chapter 4.

Figure 7.15 shows that based on the improved loader cycle time of 15.45 minutes, the loader throughputs could be increased from 5 loads/hour to 5.8 loads per hour due to increases in repair rate from μ of 0.15 repairs per hour (MTTR 6.38 hrs) to a new repair rate of μ 0.22 repairs per hour (MTTR 4.5 hrs).

(11) Therefore, similarly for a fleet of 23 production loaders at throughput rate of 5.8 loads/hr at new repair rate of 0.22 repairs per hour, an average bucket factor of 6.5 tons/bucket and 46% daily utilized hours for 30.5 days per month (336 hrs./month), this is equivalent to **291,969** tons/month or **3,503,639** tons/year. This is an additional **40,271** tons (16%) above the existing rate of 251,698 at 5 loads/hr at old repair rate of 0.15 repairs per hour.

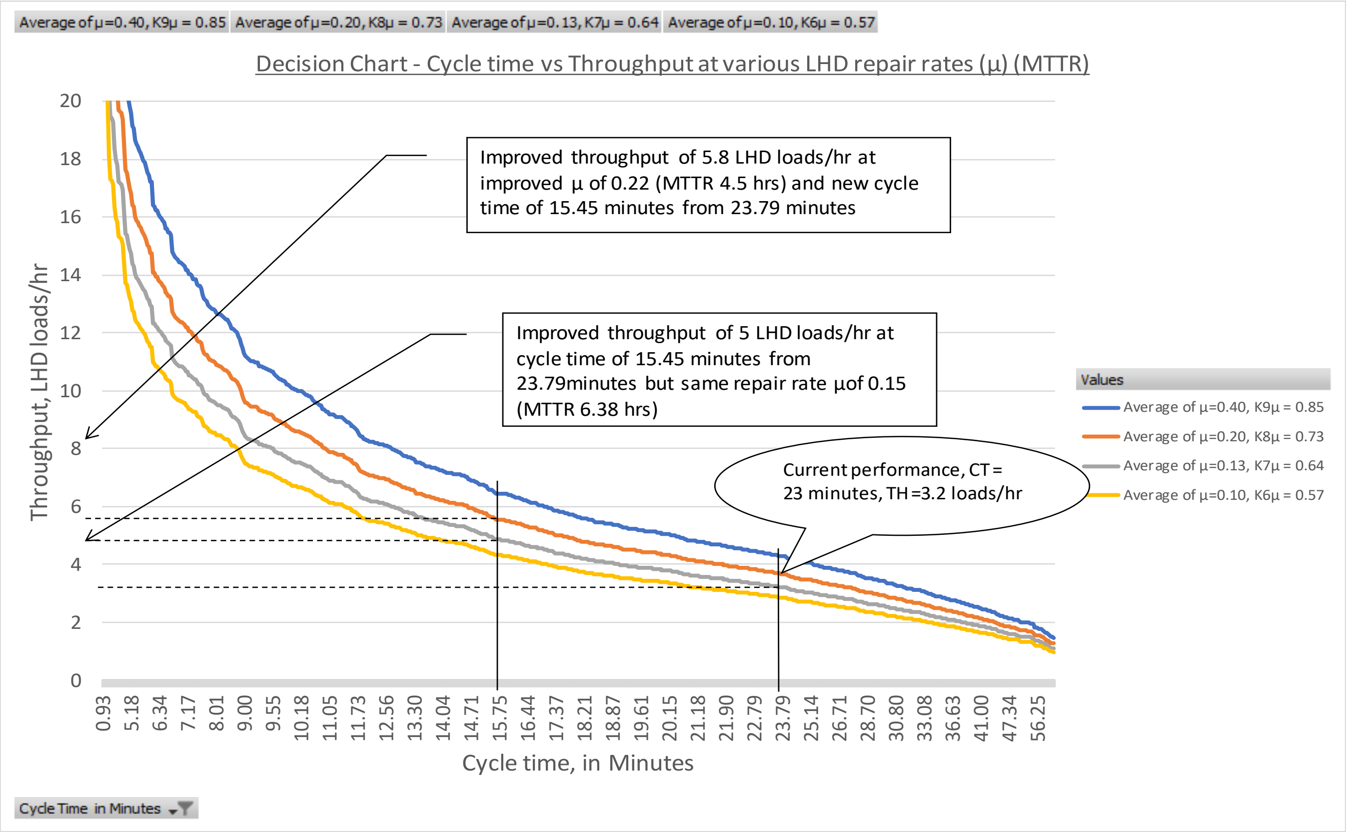


Figure 7.15 – Decision chart for improved plant repair turn-around (reduced MTTR, increased μ)

<u>Improvement-5</u>: **Improvement in maintainability through reduction in MTTR and increasing the repair μ giving an extra 40,271 tons/month and annually 483,252 tons.**

7.3. IMPROVED UTILIZED HOURS THROUGH REAL-TIME DECISION SYSTEMS

7.3.1. Critical operational activities for trackless mining monitoring

From the Chapter 5 analysis, the study found that the trackless mining consists of a complex interaction of many activities. These activities can be divided into activities which happen before at the start of a shift (SOS), those which happen during the shift (In-shift activities), those that happen at the end of shift (EOS) and engineering/maintenance activities. Decisions about which key activities to monitor and control effectively can be very important in unlocking the value in a production system

A brainstorming session with some of the key stakeholders such as mining captains and engineering supervisors identified 66 common activities. Heat maps Table 5.1, 5.2 and 5.3 indicated the activities which would give greater impact to the process if they are made visible.

An analysis of the various activities shows that effective face time can be achieved through improved monitoring of the key value adding and non-value adding activities. A practical strategy would be to identify all the non-value adding activities and classify them as non-value adding necessary or non-value adding not necessary. Those which are not necessary should be eliminated and can be set as alarms to the supervisors if they appear more frequent in the process.

7.3.2. Activity analysis – process visibility and decision making

The process for activity analysis commences by first identifying and setting the boundary of the system to be analyzed. From there the context diagram is developed which highlights the interacting systems with the system under study, as illustrated in Chapter 5, Figure 5.8. The analysis requires that the context diagram be further broken down into sub-systems which make up the actual mining processes. The sub-system process charts represented by Figure 5.10.

The mining of ore is a dynamic process hence it requires that a dynamic modeling of the activities needs to be done. The dynamic modelling was done with the use of state charts and enhanced functional flow block diagrams (eFFBD) which illustrates the different behavior patterns of the system in the different states. This is illustrated by Figures 5.11, 5.12, 5.13, 5.14, 5.15, 5.16 and 5.17. These diagrams summarize the dynamics of the different mining activities and processes.

The decision-making processes for the different states were detailed on the state transition charts Table 5.9 and Appendices C1 and C2. Through the state transition lists, it was possible to assign the different roles to be performed by the different experts in the system and how these can be used to reduce operational delays.

From the state transition lists, different roles could be partitioned between those that can be performed by human, those to be performed by machines, and those informational roles which can improve operational decision making. Informational roles are very critical for decision making.

Table 7.5 illustrates how state transition list are used to assign the different roles for mining operations during the shift.

Appendix D1 and D2 gives details of the improved state transition lists for the various operational phases of the mine indicating the assignment of new roles to the various activities. The Appendices D1 & D2 are used for indicating when the roles are purely manual and situations when real-time decision support infrastructure is available. This shows how the assignment of roles is very important for configuring a real-time decision support control system.

Deductions from the state transition list Table 7.5 show that the manual system had only four roles that are informational, whereas an improved system could have up to 23 roles which could be automated or have a real-time monitoring benefit. Some of the valuable benefits include:

- During start of shift, status of machines and operators/crew members available was done manually. An improved system would be able to give an electronic print-out of equipment and crew status. Crew status can be picked up easily from employee clocking systems such as biometric identifications or at the lamp room when one picks their lamps.
- Dispatch activities can also be done electronically, and supervisors can be made aware which production areas are available and where each equipment is allocated in real-time.
- Equipment health status monitoring can be made to display during the shift which machine is on breakdown and the kind of breakdown. It also allows the supervisors to know where each machine is working and the no of loads per hour as well as status of major components like engine, transmission, electrical hydraulic, etc.

The state transition/state lists analysis can also be useful to set alarms on value-adding and non-value adding activities. This can help to unlock value which could be compromised by non-value adding processes, as well as low efficiencies on the value adding process.

Table 7.6 is an activities specification for equipment operating activities from start of shift (SOS) to end of shift (SOS). These are all the activities of the operator during the shift. The table show that 32% of the shift time is non-value adding and unnecessary, 22% is non-value adding but necessary, and 46% only is value-adding time.

State Transition List - MINING OPERATIONS IN-SHIFT ACTIVITIES				Current Functional Roles			Functional Roles with Decision Support System		
Original State	Destination State	Condition	Action	Operator Role	Supervisory Role	Contol & Information Role (Manual)	Operator Role	Supervisory Role	Decision Support System (Computerized)
4.4.1	4.4.2	Start of Shift & Operator Available	Mine-Captain allocates machine to Operator		x			x	x
			Operator Carries out Pre-Start Checks	x			x		
			Display Operator/Equipment Status Information						x
4.4.2	4.4.1	End of work, or Operator on break, or Operator not at Work or Operator to gone to report breakdown	Switch off machine	x			x		
			Report to Dispatch Office	x		x	x		x
			Alert Mine Captain and Production Manager		x	x		x	x
4.4.2	4.4.3	Equipment Allocated to mining area, and LHD/Dtruck/Drill Rig Available, and Mining Services Installed, and Mining Areas made Safe	Dispatch Equipment to Mining area		x			x	
			Alert Production Manager and Mine Cpatain						x
			Display Equipment Loaction						x
			Display Equipment Health Status						x
			Display Hour by Hour Equipment Loads/Metres						x
			Display Shift Production Status						x
4.4.3	4.4.2	No Place to Mine/Ground finished, OR LHD/Truck/Drill Rig is not Available, OR Installing Mining Services OR Poor Mining Conditions/Ventilation/Gases	Send Alert to Dispatch Office	x			x		
			Alert Mine Captain and Production Manager	x			x		x
			Mine Captain Issues Instruction for new area to Mine		x			x	x
4.4.3	4.4.4	Process Malfunction / Production Delays Occurred	Switch off machine, and	x			x		
			Alert Dispatch Office, and	x			x		x
			Alert Mine Captain and Production Manager	x			x		x
			Mine Captain Issues Instruction for new area to Mine		x			x	x
			Display Downtime Information, and			x			x
			Display Lost Production Hours			x			x
4.4.4	4.4.2	Delay Resolved and Machine Released to Production	Change Equipment Status to Standby						x
4.4.3	4.4.5	Equipment Breakdown Occurred	Switch off Machine, and	x			x		
			Alert Dispatch Office, and	x			x		x
			Alert Mine Captain and Production Manager	x			x		x
			Alert Engineering Office	x			x		x
			Log Down Machine and Display Downtime Information						x
			Display/Track Lost Production Hours						x
4.4.5	4.4.1	Breakdown Resolved	Switch off Machine, and	x			x		
			Hand-over machine to Operations		x			x	
			Display Status of Machine as AVAILABLE						x
			TOTAL ACTIVITIES PER ROLE	**13**	**6**	**4**	**13**	**6**	**23**

Table 7.5 – Improved assignment of decision roles during mining operation

Through making certain interventions and monitoring the non-value adding activities, the effective operational time could be increased by up 20 percentage points. Some of these interventions through real time monitoring include:

- Reducing time at the waiting place from 52 minutes to 30 minutes.
- Reducing equipment pre-checks and refueling from 1.04 hours per machine to 30 minutes. This can be monitored tightly and interventions on any delays can be made in time.
- Reducing the time from when breakdown occurs, breakdown is reported, and time taken to attend. This can be drastically reduced by 39% through a proper monitoring and reporting system from 2.33 hours to 1.43 hours.
- A lot of the time is wasted by machine waiting. This could be a truck waiting for an LHD, or an LHD waiting for a dumptruck, or tips full, installing mining services such as water or ventilation columns, awaiting assignment by supervisor and so on. This time is non-value adding could potentially be eliminated completely. Alarms can be set to the supervisor to indicate when a production machine is just waiting. More than 50% of this time can be practically improved through better real-time decision support systems.
- Another hidden delay is when a production machine is assigned to non-production work such as carrying materials, vent-pipes or open drains, etc. This is factor which can be monitored effectively and improve on mine total throughputs.
- Using the data in Table 7.6, a total of 4.63 hours (20%) of face time could have been gained in the production system.
- Using the standard production rate of the time of 4.5 tons/hr per loader x 4.63 hours additional x 23 loaders x 6.5 tons/loader fill factor = 3115 extra tons/day. This is equal to **934,450** additional tons that was possible without any change in the machine throughput rates if only the effective loading time could be improved.

<u>**Improvement -5**</u>: **Improvements in reducing non-value adding times giving extra 934,450 tons/year due to improved monitoring of activities**

State List/Process Specification - OPERATING EQUIPMENT				Current Duration of State in Hours			Value added through Real-Time Decision Support			
	No	State	Description	Value Adding (VA)	Non-VA Necessary	Non-VA Unneccessary	Value Adding (VA)	Non-VA Necessary	Non-VA Unneccessary	
SOS Activities	4.1.1	Operator not at Work	Employee may not be at work due to shift change, employee off-sick, employee absenteesim or end of shift, and Primary Blasting		1.33			1.33		
	4.1.2	Travelling to Waiting Place	After going to changehouse and clocking in, employees travel to waiting place underground for taking of register, safety meeting and allocation of daily duties		0.69			0.69		
	4.1.3	Waiting Place and Dispatch Office	At the Waiting place and dispatch office, the status of employees available is taken, safety meeting is done and allocation of equipment and operators to mining areas is done and dispatched.		0.87			0.50		*Reduce time at the waiting place to only 30 minutes*
	4.1.4	Equipment Pre-Shift Checks and Dispatch Office	After equipment allocation to operators, Statutory Pre-Shift Equipment checks are carried out by operator to ensure machine is safe to use including refuelling of the machine.		1.04			0.50		*Equipment Pre-checks amd refuelling to 30 minutes*
	4.1.5	Travelling to Working Area	After all machine checks and refuelling, equipment is dispatched and travels to the designated working area or face		0.83			0.83		
In-Shift Actvities	4.1.6	Operating Equipment	Equipment carrying out actual productive and value adding work - Effective Time, equates to 3.1 hrs per 8 hour shift	11.13			15.76			
	4.1.7	Equipment Breakdown	Equipment breaks down, operator alerts dispatch office and subsequently engineering personnel. Operator waits until breakdown is resolved. Large time is taken between breakdown time and time breakdown is attended to (40%).			2.33			1.43	*Reduce Delays due to Reporting of Breakdowns*
	4.1.8	Operator on Standby (Other)	Operator waiting for another machine like LHD waiting for dumptruck or dumptruck waiting for LHD, operator might ave finished his mining area and has nowhere to mine, or the mining area is not yet prepared such as putting ventilation columns, water or power points for the rigs, or the area may be unsafe due to ventilation or gases, etc			4.45			2.22	*Reduce Standing time by 50% adding to effective time*
	4.1.9	Operator Solving Problem / Malfunction								
	4.1.10	Carrying out Services work	Operator carrying out necessary non-production work such as grading roads using LHDs, carrying materials to work areas, etc.			0.85			0.26	*Provide equipment for service work*
EOS Activities	4.1.11	EOS - Operator Travelling Back to Garage	End of shift, operator travels to garage, carries out end of shift checks and refuels machine		0.48			0.48		
			Total	11.13	5.24	7.63	15.76	4.33	3.91	
			% of Total Time	46%	22%	32%	66%	18%	16%	

Table7.6 – Potential improvements due to improved operational monitoring

Detailed analysis for all the other dynamic processes could be done by looking at the value adding and non-value adding activities as shown in Appendix D3 and D4. Alarms are possible to be set in these processes so that the delays can be managed within acceptable times through a real-time decision system.

7.4. PHYSICAL CONCEPT OF AN IMPROVED DSS FOR UNDERGROUND MINING

Chapter 6 considered the architecture used in improved decision support systems (DSS). Figure 7.16 illustrates the building blocks of a proposed improved DSS system. The DSS is a key enabler to achieving and sustaining some of the improvements which have been proposed in this Chapter. A functional DSS for production control must have a system for data acquisition and processing at manufacturing execution system (MES) level. Data acquisition devices and technology such as RFID tags, PLCs and HMI are very important to enable data acquisition.

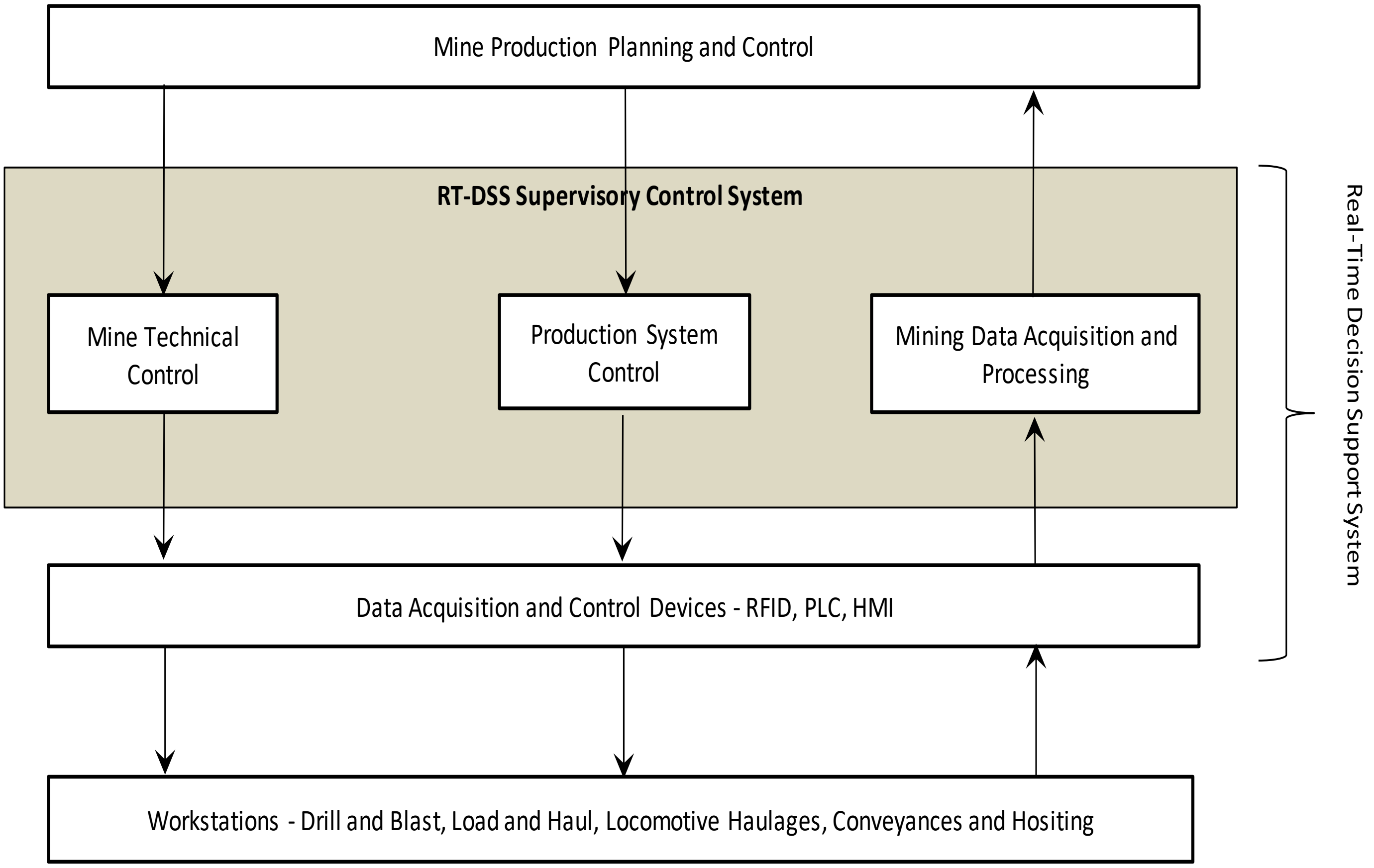


Figure 7.16 – Model of a Decision Support System (DSS) for underground

Observations carried out at MinePQR showed how an active real-time dispatch system operated in monitoring, on a continuous basis, the performance of the loading operations. It is possible with current technologies available to track machines underground as well as people and monitor all their activities throughout the shift. Critical alarms can be set to alert the right supervisory management teams to intervene where an activity is now infringing on production output.

A proposed Mine Expert Decision Support System (ME-DSS) which allows advanced decision making can be configured in the format of Figure 7.17. The system must work by first formatting the real-world static models of the production system using the different modeling tools such as the IDEF0 diagrams and process flows, etc. The static charts and eFFBD and other tools can be used to formulate the dynamic behaviour of the various systems. These models can then be loaded into an appropriate software upon which decision on the operations can be benchmarked.

The proposed expert system will then operate by monitoring the production system through the different interfaces which include the supervisors, operators and experts such as engineers. Advanced system may include expert computer systems. Both the human and computer expert systems can then be used to diagnose production problems in real time and issue and command instructions to resolve the identified problems and deviations.

Figure 7.18 illustrates how the system architecture of such an expert DSS can be configured in practice. At the core of the system will be a manufacturing execution system (MES) which integrates both the high level mine ERP system, the mine planning system (MRP), the maintenance system (CMMS) and the supervisory control dispatch system (DSCS). Also critical to this DSS is the need of a mine operations control centre on surface and the supervisory control dispatch office underground where team decisions and real-time monitoring of activities is done.

Finally, another important outcome from the analysis in Chapter 6 was the results of the on-line survey done by researcher. From the seven responses received from an online questionnaire Appendix E it was possible to illustrate that there are opportunities still to be exploited in existing trackless operations, especially here in Africa, to implement new technologies that aid and improve real-time decision making.

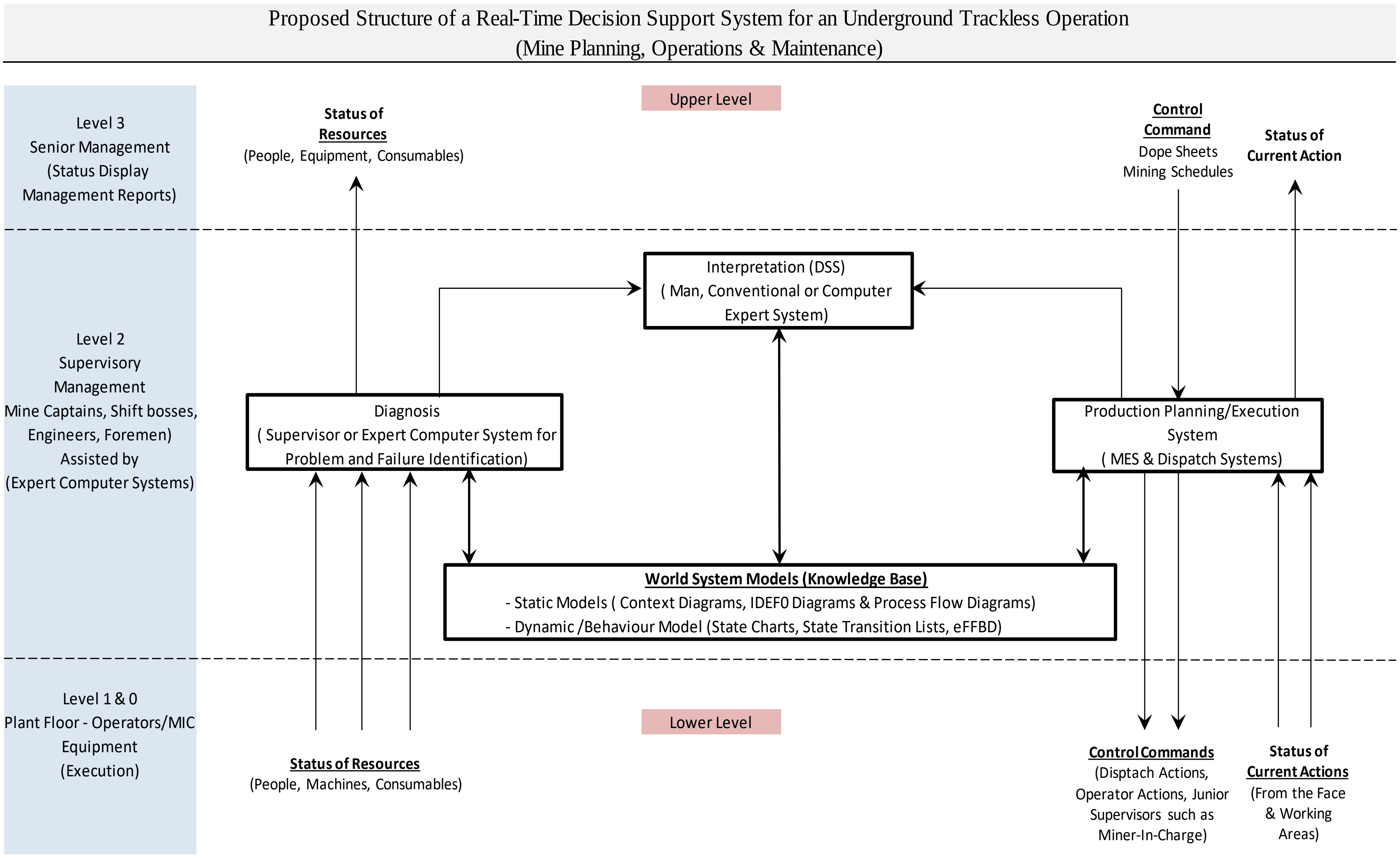


Figure 7.17 – Proposed mine expert DSS for continuous operational monitoring

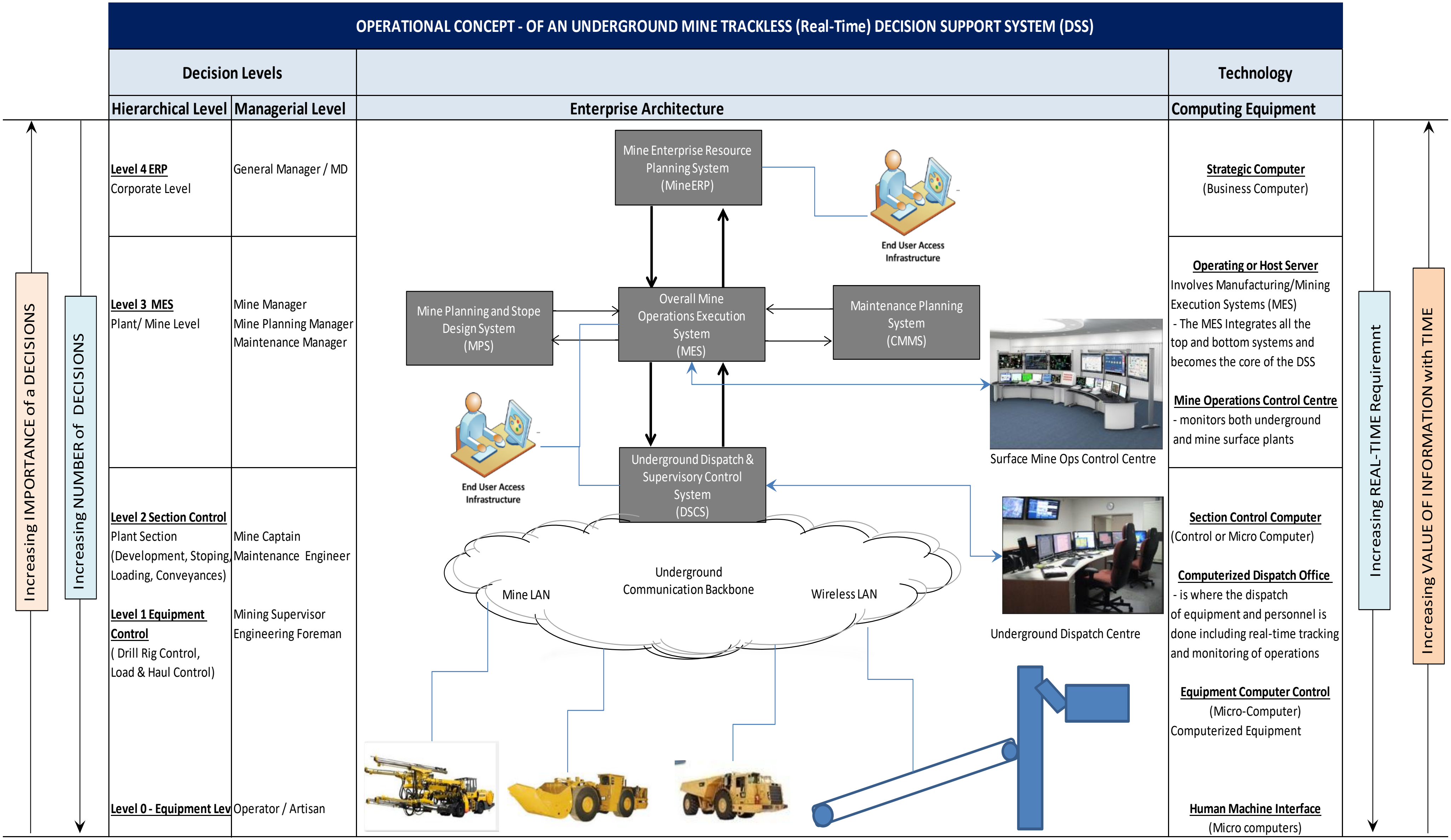


Figure 7.18 – Concept of a Real-Time Decision Support system for Underground trackless mining system.

7.5. SUMMARY OF POTENTIAL BENEFITS

Following the various analyses, the following summary gives the total potential benefits that this analysis shows could have been possible at MineABC in 2015. Year 2015 had very low metal prices and value could only be unlocked through improving the total tonnage from the mine.

Figure 7.19 shows the potential tonnage which could possibly have been generated by the intervention Improvements 1 to 5. Details of the calculations are in Appendix D5

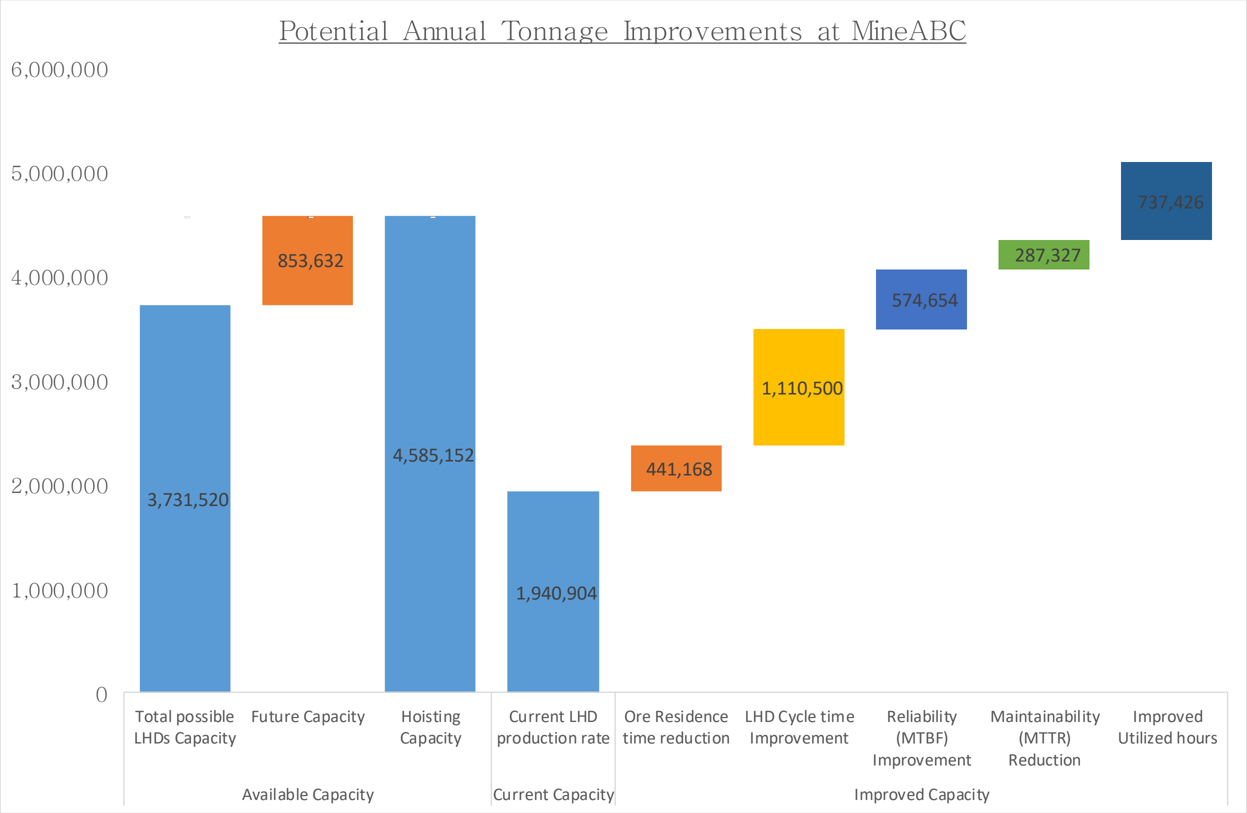


Figure 7.19 – Potential tonnage improvements due to production interventions

The five improvement areas were:

- Reduction in residence time of the ore in the system (system lead time) from 7.8 days to 5.1 days. Such an intervention would involve structuring the whole mining process to ensure that downstream bottlenecks are removed and that there is enough buffers in the system to hold the ore underground.

- The next most important and probably the one which could give real and immediate results is the reduction in LHD cycle times. This involves good co-ordination with the mine planning departments so that draw-points for ore are structured to limit the loader tramming distances. A combined reduction in the gross cycle times through the reduction in net cycle time could probably unlock up to 1,1 million additional ore tons. This is on the assumption that the drill & blast process has excess capacity to generate such amount of ore. This could not be tested in the study due to time constraints.

- A very important technical factor which could unlock the value is the improvement in the mean-time between failure MTBF of the loaders, which is an improvement in the plant reliability. Improving the MTBF from 15.82 hours to almost double of 27.12 gives a great improvement in loads per hour of 1.6 loads/h per LHD. A good way of improving the reliability of the loader includes looking at the failure patterns to develop better repair/rebuild/replace tactical decisions. A potential decision chart is shown by Figure 7.14.

- The next improvement potential is on reducing the mean time to repair MTTR. The MTTR which represents the maintainability is usually influenced by issues such as response time of the maintenance teams to a breakdown. A potential improvement of 0.8 loads/h per LHD possible by reduction in the response and repair time.

- High potential improvement also lies in improving the total effective operational time. The improvement in overall operational time means that the equipment utilization increases and the number of hours a machine is doing value adding work is increased. The way to increase utilization lies in minimizing the non-value adding and unnecessary activities. One practical way proposed is to ensure that the non-value adding, and unnecessary activities are monitored continuously. Alarms can be set in the DSS to ensure that operational supervision management can act on a continuous basis to eliminate these activities.

Table 7.7 and Figure 7.20 show possible benefits that can be obtained through the interventions 1 to 5 discussed above. The Figure 7.20 is an illustration of the possibility of exceeding the breakeven tonnage through one or two of the proposed interventions.

Potential Revenue Table

(Based on the Profitability Equation 4.10)

Area	Source	Monthly Additional Tons	Cummulative Monthly Tons	Cummulative Annual Tons	Annual Revenue (US$)	Cost (US$)	Profit (Loss) (US$)
Current	Current LHD production rate	161,742	161,742	1,940,904	8,784,070	8,730,945	53,124
	Breakeven production rate	218,000	218,000	2,616,000	21,507,842	21,507,581	261
Addition	Ore Residence time reduction	36,764	198,506	2,382,072	16,238,588	16,335,568	(96,980)
	Gross cycle time improvements	57,224	255,730	3,068,759	34,719,396	33,761,522	957,874
	LHD Cycle time Improvement	92,542	348,272	4,179,260	87,696,392	76,345,368	11,351,025
	Reliability (MTBF) Improvement	47,888	396,159	4,753,914	129,073,637	105,369,845	23,703,792
	Maintainability (MTTR) Reduction	23,944	420,103	5,041,241	153,920,327	121,669,439	32,250,888
	Improved Utilized hours	61,452	481,556	5,778,667	231,828,371	168,955,893	62,872,478
	Maximum Potential Total	319,814	481,556	5,778,667	231,828,371	168,955,893	62,872,478

Profitability Equation, $P = 1.73x10^{-10}.\,Q^3 - 8.66x10^{-5}.Q^2 + 13.96.Q - 7.2 \times 10^5$, Q=Monthly Tonnage (4.10)

Table 7.7 – Potential revenue from proposed production interventions

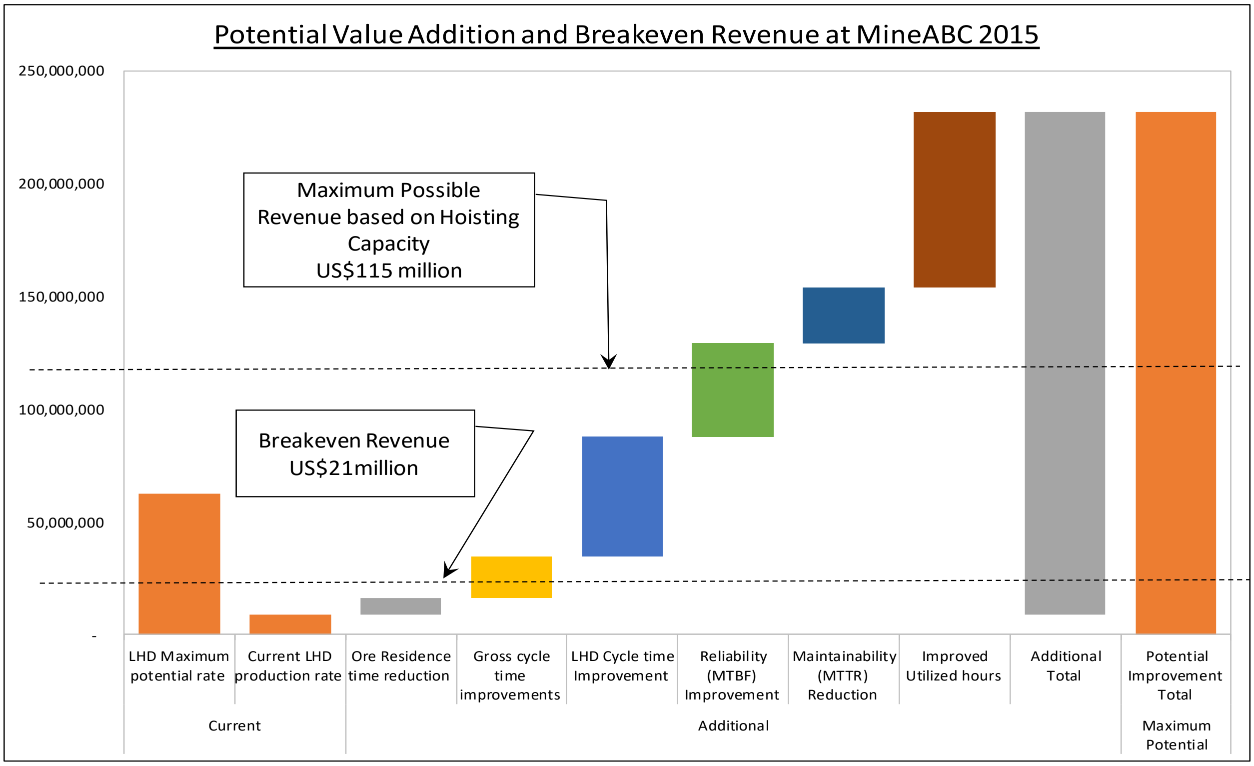


Figure 7.20 – Potential revenue improvements corresponding to Table 7.8

8. CONCLUSIONS AND RECOMMENDATIONS

8.1. CONCLUSIONS

This study was based on the hypothesis that there are opportunities to maximize production outputs in many existing underground hard rock trackless mining systems using the same or less resources by improvement in decision making paradigms. The need to improve productivity and efficiencies in the mining industry is becoming a very important value driver as the uncertainties and continued drop in metal prices are becoming the new normal of the industry. The project main goal was thus to carry out a detailed investigation to test how mining production can be maximized.

The study showed that total production output from an underground trackless mine can be maximized through three main factors of either increasing the production rates in terms of tons per hour, through maximizing the effective operating hours of the trackless equipment underground, or through improving the quality of ore. Although quality factors such as fragmentation are vital, they were not considered in this study and would normally require separate analysis.

Three objectives set for the study to address the two factors of production rates (tons/h) and total effective utilized hours (h), namely: (1) to carry out an analysis of key technical factors that impact the production rates in a trackless mining production system and setting decision criteria on those, (2) to identify major operational activities which impacts on effective mining equipment operating times and how improving visibility of the operations through decision support systems (DSS) can improve production outputs, and (3) illustrate how a DSS architecture can be configured for improving decision support.

Due to the impracticality of carrying out an experimental study in a trackless underground mine, the study was designed as a non-experimental observational (correlational) research involving case studies, use of historical archival data and use of online research tools to meet the objectives.

A selected large copper and nickel mining operation where the researcher was employed was used as the main case study mine where detailed observation of mining activities and tasks was done as well as detailed analysis of historical operational data and business information. An on-line survey was used as a benchmark to validate some of the results as well as to check the extent of how decision support systems are used in the underground hard rock mining industry.

Trackless mining is a process where rubber tyred diesel powered hydraulic equipment and machinery is used underground for carrying out the mining activities. Due to the lack of specific literature describing the dynamics of trackless mining production systems, the trackless system had to be modeled as a quasi-manufacturing system. Through this modeling, the principles which govern a manufacturing process, where a lot of detailed research information is available, were used in the analysis.

The mine under study had four deep level vertical shafts and therefore the mine production system was thus modeled as a serial production system with five key work stations for each shaft (see Figure 7.2). The work stations were drill and blast, load and haul, tramming, crushing and conveyance and hoisting. The main value driver was to maximize the mine system throughput which in this case was the hoisted tons. Mathematical methods for analysis of the dynamics of stocks, material in transit, system delays and factors which impact throughput of production lines were used to carry out the analysis of the production system.

The approach to the analysis was to analyse the production system by first decomposing the system from high level, to process level, and then to component/equipment level and develop solutions at these levels. The overall system level solution which drives the mine value is then assumed to the found through integrating the different solutions to get the overall benefits.

Therefore, the ore mining system was then first analysed at system level, then at process or work station level, followed by equipment level. For maximizing the production rates in terms of tons per hour, the major finding from the study was that this can be maximized through one system level factor, one process level factor and three work station/equipment level factors.

The important system level factor which needs to be optimized is the reduction of residence time of the ore in transit in the mine. The study found out that the ore in transit from blasting of the ore until the ROM pad was taking an average of 7.38 days and there were thus opportunities to reduce this value to as much as 5.81 days through reducing some of the non-value adding processes. A decision chart was therefore developed which could be used to determine the impact of reducing the ore residence time. This could be achieved through appropriate planning of the buffer or ore storage and transport systems underground. This is a more strategic and tactical decision.

The study showed that process level decisions are mainly centred around the factors which impact the various work stations and balancing the flow process to remove any constraints in the system. In this case a process level analysis through theory of constraints (TOC), load balancing and value stream mapping of the process showed that the drill & blast; and the loading process were the main constraint to the mine. This was proved through the gross cycle times which for the loading process was 93% higher than Takt time. The Takt time is a key decision factor as it illustrates the maximum cycle time allowed by an operation to meet daily demand. In this case the Takt time in the loading process was supposed to be 226 seconds per ton, but the mine was operating at 437 seconds to produce a ton of ore. Therefore, it was shown that a key decision factor would be to work on reducing the gross cycle time of the LHDs which were a major constraint to the whole process.

Similarly, the gross cycle times for drill and blast works station, and for truck hauling were all above the Takt time hence being process constraints. Hence further analysis could still be done to optimize these processes.

The study also proved that three factors which impact the capability of the mining equipment are those centred around the equipment performance in terms of equipment reliability, maintainability and design capacity through the cycle time. The reliability of the equipment was measured by failure rates and mean times between failures (λ, MTBF) and the maintainability is measured through the repair rate and the mean times to repair (µ, MTTR). Since the LHDs were identified as a major constraint, a detailed equipment level analysis was thus done on the loaders.

It was found that the equipment capability in terms of loads per hour can vastly be improved through reduction of the LHD cycle times. The most practical way of doing that is through minimizing and limiting the tramming distances of the loaders. The LHD cycle time could be reduced from the average of 23 minutes per load to 15 minutes per each load. This could potentially unlock up to an extra 1.1 million tons of ore annually, in the absence of other constraints.

Two decision charts were developed to use for determining the optimum MTBF and MTTR factors which can unlock and improve production rates. It was shown through the study that reduction in rate of failures and improvement in repair rates could unlock combined extra 862000 tons annually. Reliability of equipment can be improved through analyzing the equipment failure patterns and developing appropriate bath tub curves/Weibull charts so that appropriate repair/rebuild and replace decisions can be made. Maintainability could be improved by reduction of response times.

The last significant factor to improve production outputs lies in understanding the factors which impact the overall utilization of the equipment. This can be vastly improved by fully monitoring all the activities which make up the total time in a mine and deliberately intervening to remove non-value adding activities. The study finding, and proposal is that this can best be achieved by implementation of an active real-time decision support system (DSS). A modern and active DSS can be able to monitor in real-time most of the activities underground which would not be visible to the line supervisors during the shift and alert any delays in the key mining activities.

A dynamic analysis of the mining activities was done using the state charts and eFFBD and these were able to reveal some of the non-value adding and unnecessary activities which can be continuously monitored to improve mine effective operating time. Over 700 000 tons of extra ore could be unlocked in the system if the LHDs' value adding operating time could be increased from 11 hours per day to 15 hours per day.

In overall, improvements in production outputs in a mine can be realized through focusing on system level, process level, equipment level and operational level decisions. If a mine is to invest in new technology for decision support (DSS), it will be highly recommended to consider the above factors and their impact to the overall system value. The study was able to show that by implementing some of these proposals, the mines under study could have operated above the breakeven tonnage even in the low commodity price regime it was operating in during the year 2015 by focusing on data driven productivity improvements methods.

8.2. RECOMMENDATIONS FOR FUTURE WORK

Based on this study, the following recommendations are put forward as an approach and a way which can be applied in productivity improvements in underground trackless mining systems:

1. When implementing a productivity improvement project in underground trackless mining systems, the research recommends to apply a Lean Systems Engineering (LSE) approach where system engineering techniques are used in analysis of the problem and lean/operational research tools are used in defining and developing scientific solutions.
2. For a trackless production system, the analysis must look at factors which have impact on throughput rate, and on those factors that have an impact on the effective operating time based on the production equation (1.1).
3. Future works must also focus on applying of manufacturing theories in analysis of underground mining systems. The research recommends that a trackless mining production system is best analysed when it is looked at as a serial production system, which makes it plausible to apply throughput analysis theories as in a manufacturing process.
4. However it is also strongly recommended that underground mining environmental factors must be taken seriously into consideration when doing a throughput analysis for such a mining system as they are expected to have a significant impact on the results. Simulations and analysis of these factors such as heat, water, humidity, operator behaviours, geological challenges and continuously changing boundaries which are unique in underground operations are some of the factors which presents themselves for further research work and could not be fully simulated in this study.
5. When analysing the system, problems, shortcomings and requirements should be defined at system level, sub-system level/process level and at component/equipment level. This should be done through decomposition of the problem from higher level to lower levels and then integrating the solutions.
6. Figure 7.2 shows a recommended framework for analysis of throughput in a trackless production environment.
7. Figure 7.2 also shows that at system level, the recommended approach would be to analyse overall system delays using mathematical approaches and tools such as analysis of material in transit, stocks and material delays, as well as the operational delays which emanates from

operating and maintaining equipment in the system. Understanding of system delays will allow optimization of the buffers and internal stockpiles in the whole production system. Also at system level the overall system lead time is very crucial including identifying value adding and non-value adding time. A value stream map is very useful tool to use in this regard.

8. At sub-system or process levels, it is important to apply tools such as the theory of constraints (TOC), analysis of gross cycle times and production load charts. Production load charts are produced by calculating the TAKT times and Gross cycle times for each work-station. These gross cycle times are useful in identifying areas of the process which are constrained and those with extra capacity.
9. The next recommended level is to analyse the system delays at workstation and equipment levels. At this level, reliability and maintainability analysis is very critical to be able to calculate the actual work station capacity versus the theoretical/nameplate capacity. Maintainability and reliability factors have a huge impact to overall throughput from each work station. Decision charts were developed in this research which the researcher recommends to be developed whenever a study of this kind is being undertaken. These charts shows the impact of cycle time, failure rate (λ) and repair rates (μ) on the station throughputs and how varying each of these can have huge impact on a production station capacity.
10. Finally, the third important factor is the analysis of the effective face time of a trackless mining operation. The use of activity analysis and dynamics behaviour of the process for real-time control is very crucial. The use of IDEF0 diagrams, eFFBD, State Charts and State Lists help in specifying the requirements for real-time operational control.
11. Finally, Figure 7.18 is shown as a framework for development of a real-time decision support system. The system shows how a manufacturing execution system (MES) can be used to integrate the ERPs, MPS and the CMMS for real-time control of operations. This requires an effective communications backbone underground to achieve this. The specifications list developed from activities analysis should be used as the inputs in configuring the DSS.
12. The key to a functional DSS will be the development of the MES as the integrating system. This work is now of much interest to mining system development companies as there is increased development in the use of big data and analytics. The use of analytics, big data and artificial intelligence will be part of the integrating execution system as data is being generated from different sources such as equipment software, HMI, SCADA systems, etc.

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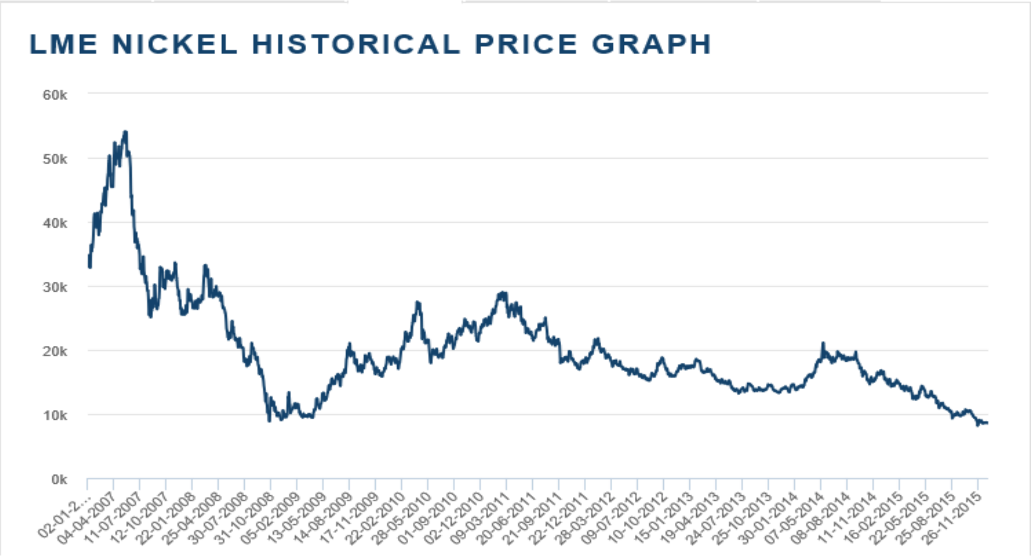
APPENDICES

A. Chapter 1

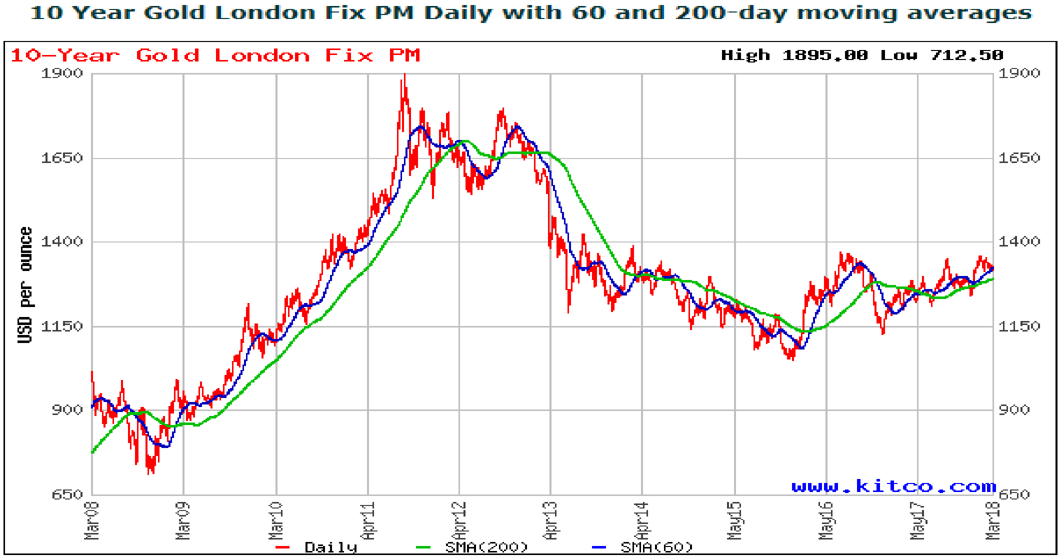
A.1. Historical Nickel, Copper and Gold prices charts

Historical Nickel Price Charts

(extracted 07/01/2018 - https://www.lme.com/en-GB/Metals/Non-ferrous/Nickel#tabIndex=2).



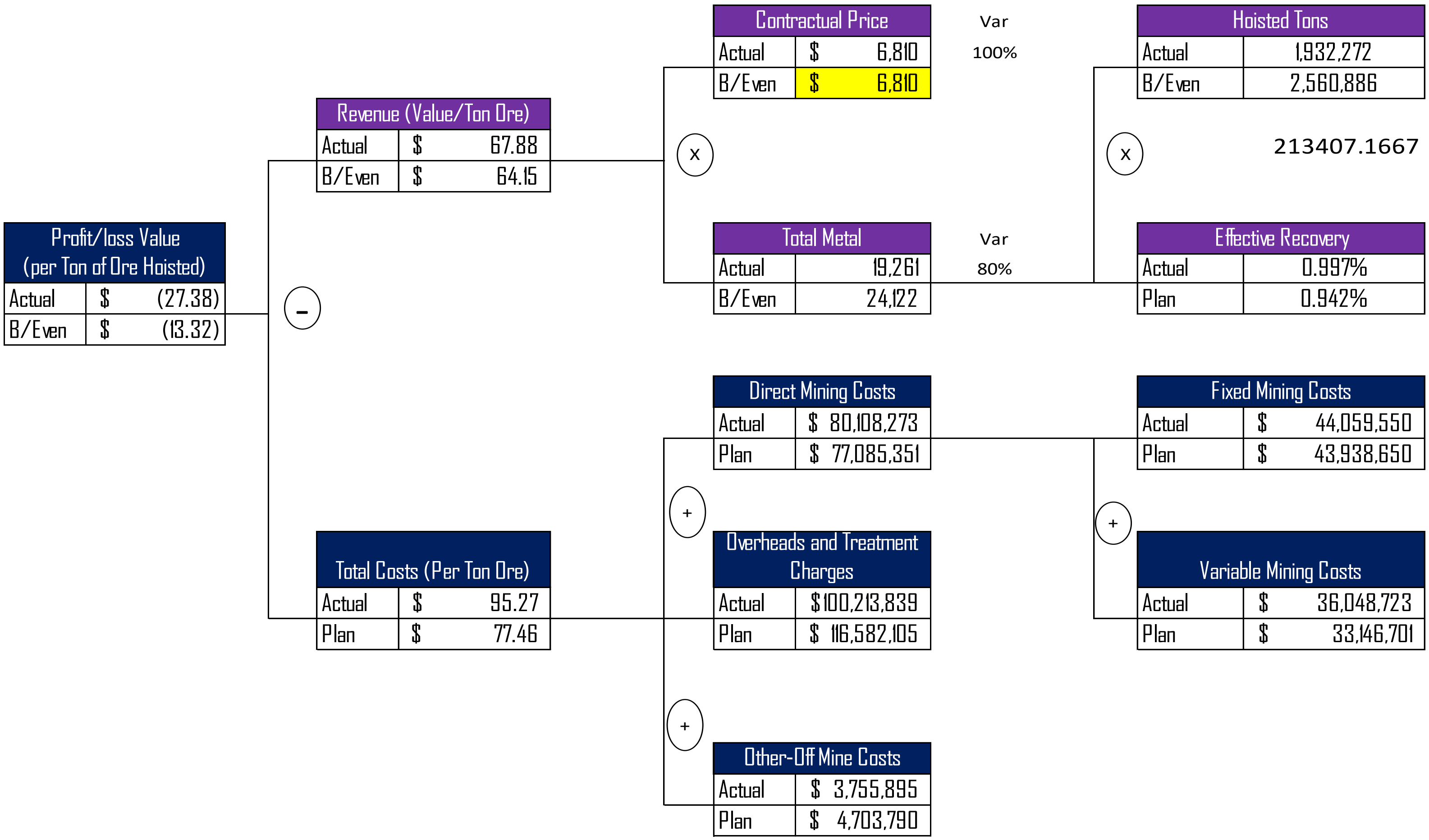
Gold Price History: (Extracted on 27/3/201 : http://www.kitco.com/charts/historicalgold.html)



B. Chapter 4

B.1. VDT for prevailing prices in 2015 at budgeted production target.

MineABC tonnage at 2015 Prevailing Prices and Costs



Profit/loss Value (per Ton of Ore Hoisted)		
Actual	$	(27.38)
B/Even	$	(13.32)

Revenue (Value/Ton Ore)		
Actual	$	67.88
B/Even	$	64.15

Total Costs (Per Ton Ore)		
Actual	$	95.27
Plan	$	77.46

Contractual Price		
Actual	$	6,810
B/Even	$	6,810

Total Metal	
Actual	19,261
B/Even	24,122

Hoisted Tons	
Actual	1,932,272
B/Even	2,560,886

Effective Recovery	
Actual	0.997%
Plan	0.942%

Direct Mining Costs	
Actual	$ 80,108,273
Plan	$ 77,085,351

Overheads and Treatment Charges	
Actual	$100,213,839
Plan	$ 116,582,105

Other-Off Mine Costs	
Actual	$ 3,755,895
Plan	$ 4,703,790

Fixed Mining Costs		
Actual	$	44,059,550
Plan	$	43,938,650

Variable Mining Costs		
Actual	$	36,048,723
Plan	$	33,146,701

B.2. MineABC Production and operating profit data 2013 – 2015

		Dec-13	Q3-2013	FY-2013	Feb-14	Q1-2014	Dec-14	Q3-2014	FY-2014	Dec-15	Q3-2015	FY-2015	
Period		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	Total
Hoisted Tons	Shaft-A	70,612	67,501	61,314	59,642	58,247	47,316	54,639	56,324	43,537	50,465	54,429	624,026
	Shaft-B	13,017	18,662	26,712	22,290	17,640	24,038	22,480	22,745	18,510	19,724	22,190	228,008
	Shaft-C	39,128	41,425	40,276	32,800	31,762	47,149	42,138	41,942	37,992	38,740	41,700	435,053
	Shaft-D	51,622	51,555	49,021	42,586	44,998	45,268	46,148	46,823	37,188	38,304	42,704	496,217
	Hoisted Tons	174,379	179,143	177,323	157,318	152,647	163,771	165,405	167,835	137,227	147,233	161,023	1,783,303
Contained Nickel	Shaft-A	341	332	283	331	310	192	225	262	219	240	260	2,996
	Shaft-B	135	199	268	251	193	196	221	81	171	190	210	2,115
	Shaft-C	170	196	193	140	137	228	202	198	181	181	206	2,031
	Shaft-D	400	436	348	374	388	283	302	347	366	328	347	3,919
	Total	1,046	1,162	1,092	1,096	1,028	899	951	888	937	939	1,023	11,061
Contained Copper	Shaft-A	364	329	295	314	283	171	202	239	200	211	216	2,826
	Shaft-B	93	136	193	161	122	133	150	144	123	132	146	1,533
	Shaft-C	259	292	298	271	256	398	357	368	397	374	413	3,682
	Shaft-D	367	401	312	328	332	253	297	313	324	285	291	3,503
	Total	1,084	1,159	1,098	1,074	994	955	1,007	1,064	1,044	1,002	1,065	11,545
Total Metal produced		2,191	2,084	1,984	819	898	2,130	2,534	1,606	1,953	1,002	1,605	18,805
Effective Recovery		1.26%	1.16%	1.12%	0.52%	0.59%	1.30%	1.53%	0.96%	1.42%	0.68%	1.00%	1.05%
Unit Cost - Ore Hoisted -	Shaft-A	37	35	32	22	36	38	26	74	53	43	25	38
	Shaft-B	50	45	34	27	43	42	30	91	58	49	33	46
	Shaft-C	25	29	28	22	39	39	26	56	43	35	23	33
	Shaft-D	25	24	20	20	24	32	24	47	35	29	22	27
	Unit Cost - Ore Hoisted	34	33	28	23	36	38	27	67	47	39	26	36
Adjustments		1	3	12	1	2	1	3	12	1	3	12	
Operating Profit		(11,301)	(5,432)	(2,112)	(8,028)	(530)	(5,909)	(4,125)	(3,419)	(43,184)	(17,153)	(4,101)	(9,572)

B.3. ShaftA3 Drill rigs performance statistics for year 2015

Process ID	Process Description	Measure	Ore Tons	Grades		Metal Tons	
				Ni	Cu	Ni	Cu
1.1	Insitu Rock - Drilled Reserves						
	Phikwe Central had 22.3 million known reserves for #1-Shaft and #3-Shaft combined at average grades of between 0.54 - 0.72% Nickel and 0.45 -1.07% Cu	Measured, Inferred and Indicated Resources	32,994,452	0.62	0.7	180,145	155,782

Drill Rigs Performance for Yr 2015

Process ID	Process Description	Measure	Actual	Required as per Budget	% Var	Unit
1.2	Generate Ore by Breaking Ground	Holes drilled per Drill Rig/day	60	88	-33%	Holes
	Total Tons of Ore Moved in 2015 (73% of Budget)	Total Holes drilled per day	298	442	-33%	Holes
		Metres drilled per Drill Rig/day	220	326	-33%	tons
	In 2015, PC used 4 Face Drill Rigs and 1 Long-hole rig to generate ground. Each face drill rig operated for a total of 1.78 percussion Hrs per day against a target of 7.57 hours per day	Metres drilled per Drill Rig/Month	5,719	8,482	-33%	tons
		Tons Generated per Rig/day	391.0	580.0	-33%	tons
		Tons Generated per Rig/Month	4,692.5	15,080.0	-69%	tons
		Total Tons Generated by all Rigs per day	1,955.2	2,900.0	-33%	tons
		Total Tons Generated by all Rigs per year	610,026.4	904,800.0	-33%	tons
		Percussion Hour/day/Rig	2	8	-76%	Hrs
		Cycle time, minutes to drill a hole	3	2	55%	mins/hole
		Throughput Time, hrs to generate 2900 tons/day	6.17	9	-31%	h (2900 tons)
		Throughput rate, metres/HR	19	30	-36%	Metres/HR
		Value-Added Time	6.17	13.2	-53%	Hrs/day
		Drills Availability	0.9	0.9	1%	%
		Drills Utilization (Percussion)	0.1	0.4	-77%	%
		MeanTime Btn_Failures	23.5	40.0	-41%	Hrs
		MeanTime to_Repair	4.3	6.0	-28%	Hrs
		Availability Index (MTBF/(MTBF+MTTR))	0.8	0.9	-3%	
		EffDownHRs/Day/Drills	6.6	3.3	100%	Hrs
		RepairHrs/Day/Drills	6.1	3.3	86%	Hrs
		Cost/ton of Ore	$ 0.68			$/ton
		Cost/hr	$ 47.40			$/ton

B.4. ShaftA3 Mine Loaders (LHDs) performance statistics for year 2015

Mine Loaders (LHDs) Performance for Yr 2015

Process ID	Process Description	Measure	Actual	Required as per Budget	% Var	Unit
		Total Tons Moved in 2015	655,578	904,800	-28%	tons
1.3	Total Tons of Ore Moved in 2015 by LHDs was 73% of Budget	Total Tons Moved per Day	2,101	2,900	-28%	tons
		Tons moved per LHD/day	170	235	-28%	tons/LHD
		Tons moved per LHD/Month	4,419.0	6,099.0	-28%	tons/LHD
	All the ground which is moved is what the LHDs can move. In 2015, 13 x LHDs were used for Ore Production at PC of which each LHD is averaging only 4419 tons/month against a benchmark target of up to 18000 tons per day for a 10 ton LHD	Operating Hours Daily	8.9	13.3	-33%	Hrs
		Cycle time, minutes to move a load	15.2	16.0	-5%	mins/load
		Throughput Time - hrs to move target batch(2900 tons/day) in the system	10.6	12.2	-13%	Hrs
		Throughput rate, Loads/HR	4.0	3.7	6%	Loads/HR
		Value-Added Time	8.93	12.24	-27%	Hrs/day
		LHD Availability	73%	85%	-14%	%
		LHD Utilization	52%	65%	-20%	%
		MeanTime Btn_Failures	12.9	40.0	-68%	Hrs
	0.724545007	MeanTime to_Repair	4.4	6.0	-27%	Hrs
	0.2455	Availability Index (MTBF/(MTBF+MTTR))	75%	87%	-14%	%
		EffDownHRs/Day/LHD	11.7	3.3	255%	Hrs
		RepairHrs/Day/LHD	9.6	3.3	191%	Hrs
		Cost/ton of Ore	$ 2.90			$/ton
		Cost/hr	$ 56.89			$/hr

B.5. ShaftA3 Trucks performance statistics for year 2015

Dumptrucks Performance for Yr 2015

Process ID	Process Description	Measure	Actual	Required as per Budget	% Var	Unit
		Tons moved per Truck/day	165	409	-60%	tons
		Tons moved per Truck/Month	4,299	10,631	-60%	tons
	Dumptrucks moved 71% of the ore transported in the system per day. The rest of the ore was moved by the LHDs straight into ore tips without dumptrucks.	Fleet Tons Moved per Day	1,488	3,680	-60%	tons
		Total Tons Moved per Year	517,569	1,279,749	-60%	tons
		Operating Hours Daily	4.6	10.5	-56%	Hrs
		Cycle time, minutes to move a load	26.7	11.8	126%	mins/load
	Each trucks averages 2.2 loads in an hour and this is usually a factor of distance of the tips	Throughput Time, hrs to move target batch in the system(2900 tons/day)	9.1	8.3	9%	hrs/batch (2900 tons)
		Throughput rate, Loads/HR	2.2	5.1	-56%	Loads/HR
		Value-Added Time	4.6	10.5	-56%	Hrs/day
		Trucks Availability	83%	85%	-2%	%
		Trucks Utilization	29%	65%	-55%	%
		MeanTime Btn_Failures	17.2	40.0	-57%	Hrs
		MeanTime to_Repair	3.4	6.0	-43%	Hrs
		Availability Index (MTBF/(MTBF+MTTR))	83%	87%	-4%	%
		EffDownHRs/Day/Truck	5.6	3.3	70%	Hrs
		RepairHrs/Day/Truck	5.0	2.5	102%	Hrs
		Cost/ton of Ore	$ 0.91			
		Cost/hr	$ 29.01			

C. Chapter 5.

C.1. Shift activity analysis – HEAT MAP ENGINEERING AND EMPLOYEE DISPATCH ACTIVITIES

					RATINGS		
Ref	**ACTIVITY**	**Responsibility**	**Current Scenario**	**IMP**	**EFF**	**Priority**	**Stakeholder required future**
SP1	**AVAIL DAILY MINING PLAN - MINING OPERATIONS**						
SP1-1	Provide Monthly Plan	Tech-Services	Monthly plan provided start of month	5	**7**	**20**	Access on-line and update continously
SP1-2	Face Layouts	Tech-Services	Manual plans	5	**5**	**30**	Provide electronic geological maps
SP1-3	Mining Positional Data	Tech-Services	Need to monitor if mining according to plan, only know after survey	5	**6**	**25**	Electronic geological maps and updated continously
SP1-4	No of Ends Available to mine	Mine Supt.	Manual Handover EOS	5	**9**	**10**	Updated electronically
SP1-5	Quantity of Production in sections	Mine Supt.	Estimates/Unknown	5	**9**	**10**	"
SP1-6	Daily Mining Plan	Mine Supt.	Deciding where to mine start of shift a major challenge	5	**3**	**40**	"
SP2	**EQUIPMENT HEALTH & STATUS**						
SP2-1	Machine Status End of Shift (EOS)	Shift boss	All machines are parked in w/shop after shift except when there is a breakdown	**5**	**3**	**40**	Equipment tagging, identify location of each machine real-time
SP2-2	Machine Status Start of Shift (SOS)	Foreman	Relies on report from operators	**5**	**5**	**30**	Machine health status monitored by telemetry and displayed on supervisors computer
SP2-3	Machine Location	Supervisors	Machine location can be a challenge if machine breaks down in sections	**5**	**7**	**20**	Equipment tagging, identify location of each machine real-time
SP2-4	Daily Pre-shift Lube checks	Mechanic		**5**	**4**	**35**	
SP2-5	Daily Pre-shift Checks	Operator	Operator logging & behaviour monitoring	**5**	**6**	**25**	
SP2-6	Fuel and Lubricants status	Maint. Planning	Sometimes we run out of Fuel/Lubricants	**3**	**7**	**12**	Monitor electronically
SP2-7	Re-fuelling	Operator	Time taken for refuelling is not monitored	**5**	**5**	**30**	
SP2-8	Release machine to production	Mechanic	Machines parked haphazardly, blocked machines	**5**	**3**	**40**	Update dispatch status in real-time
SP2-9	PM - Maintenance Schedule	Maint. Planning	Schedule available but changes agreed between foreman & shiftboss	**5**	**8**	**15**	Alarms for non-compliance to schedules
SP2-10	MDE - Execute PM tasks	Foreman	PMs done on fixed time basis instead of hour/usage based	**5**	**2**	**45**	Monitor PMs electronically based on hour meters
SP2-11	Fixed Plant - Shutdown Execution	Foreman	Shutdown overuns	**5**	**6**	**25**	
SP2-12	Downtime occurance reporting	Operator & Mechanic	Breakdown is reported to clerk on surface who in turn phones w/shop. Operator must get nearest place with phone to update breakdown to clerk.	**5**	**6**	**25**	On-line equipment status reporting real-time
SP2-13	Breakdown Response	Mechanic	1.41hrs Delay per breakdown. Mechanic must get transport, assess breakdown, come back collect tools and resources and then go to fix machine.	**5**	**6**	**25**	Alarms on breakdown status continously
SP2-14	Machine availability	Maint. Planning	Conflcting information - limping machine	**5**	**5**	**30**	Electronic update of downtimes

C.2. Shift activity analysis - HEAT MAP FOR INSHIFT AND END OF SHIFT (EOS) ACTIVITIES

				RATINGS			
Ref	**ACTIVITY**	**Responsibility**	**Current Scenario**	**IMP**	**EFF**	**Priority**	**Stakeholder required future**
SP6	**SHIFT Production Status and Monitoring**		**Total SP6**				
SP6-1	Source of Production - Available Ends	Mine Supt.	Planned at start of shift	5	7	**20**	Geological map displayed real-time
SP6-2	Actual Quantity of Production in sections at a time	Mine Supt.	Planned at start of shift	5	7	**20**	Displayed real-time
SP6-3	MDE - Equipment positional data during the shift	Shift boss	Is invisible to management during the shift	5	5	**30**	Displayed real-time
SP6-4	Machine Utilization on Hour by Hour basis	Shift boss	Hourly machine utilization	5	5	**30**	Displayed real-time. Manage delays as they happen and increase utilization to target 85%
SP6-5	MDE/Locos - Hour on hour tramming information	Shift boss	Loads/hr per loader or truck only known end of shift. Machine utilization is 32% for LHDs and has room for improvements	5	3	**40**	Displayed Real-time
SP6-6	MDE - Machine down-time occurances	Shift boss	Time between occurance & reporting to engineering is average 4 5minutes	5		**55**	Give alarms and display in real-time
SP6-7	Drilling Operations - Drill actual vs plan, start drilling, drilling efficiencies, breakdown reporting and responses	Shift boss	Efficiency monitoring not being done well	5	3	**40**	Monitor real time drilling operations
SP6-8	Charging and Blasting	Shift boss	Poor advances on blasting. Misfires. Lost blasts	5	3	**40**	Central blasting system and hook on telemetry. Target 10% improvements in advances
SP6-9	Crusher production & status - monitoring ofcrushers, TPH (actual vs planned), V-belt alignment, tension, vibration, roof bolts, etc.	Shaft Supt	TPH being monitored on the discharge conveyor, monitoring of crusher condition is done by an operator on the crusher	5	10	**5**	Display real-time including monitoring of crusher health - motor amps, chute blockages, vibration, etc.
SP6-10	Conveyor belts production & status - monitoring of TPH (actual vs planned), belt alignment, tension, damage, chute blockage, skirting, rubbers, roof bolts, spillages, etc.	Shaft Supt	2 x Serious belt cuts occurred in a year including cut on a new belt which had to be discarded	5	7	**20**	Use telemetry to monitor belt condition real-time including protection against cuts.
SP6-11	Hoisting - production monitoring & status - TPH (actual vs planned), No of skips, hoisting time	Shaft Supt	Hoisting time is expected to be 8hrs/shift but actual is usually btn 6 to 7hrs. 1 hr lost daily. Daily total hoisting time need continous monitoring	5	10	**5**	Monitor hoisting real-time from start to finish time. Give alarms if there are delays in hoisting time. As much as 20-50% time saving is possible
SP6-12	Silos - Levels of Surface bin, underground silos and tips	Shaft Supt	Silos and bins gives buffers in cases of breakdowns and status of bins monitored electronically.	5	10	**5**	Need to be intergrated in the total process monitoring system
SP7-1	Manual blasting from surface	Shift boss	Challenges of misfires and clearing of personnel from underground	5	10	**5**	Centralized blasting with monitoring
SP7-2	Secondary Blasting		Challenges with clearing people from bottom levels, takes a lot of time	5	4	**35**	Geological visualization of the areas to be blasted and make safe people in the area.

C.3. State Transition List for Operating mining equipment

State Transition List - OPERATING EQUIPMENT				Current Functional Roles		
Original State	Destination State	Condition	Action	Operator Role	Supervisor Role	Contol & Information Role (Manual)
1.1.1	1.1.2	Start of Shift & Employees Arrive at work	Employees go to Changehouse and proceed to Lamproom	x		
1.1.2	1.2.1	Employee Clocked In	Employees Collect Cap-lamps & rescue packs	x		
			Employees Waiting for Cage	x		
			Employees proceed to waiting place	x		
			Generate Report and Alert Mine Captain and Production Manager on Employees Status		x	
1.2.1	1.2.2	Operator Available	Toolbox Safety meeting		x	
			Allocate machines to Operators and work areas		x	
			Proceed to Garage and carry out pre-shift checks		x	
			Display Equipment Health Status			
1.2.2	1.2.3	Equipment Mechanically OK and Refuelled	Travel to Working areas	x		
1.2.3	1.3.1	Mining areas ready	Proceed to carry out mining activities	x		
1.3.1	1.3.3	Equipment Breakdown Occurred	Switch off Machine, and	x		
			Alert Dispatch Office, and	x		
			Alert Mine Captain and Production Manager	x		
			Alert Engineering Office			x
			Log Down Machine and Display Downtime Information			x
			Display Equipment Status as Breakdown			
			Display/Track Lost Production Hours			
			Mine Captain gives instruction to re-arrange production		x	
1.3.3	1.3.1	Breakdown Resolved	Hand-over machine to Operations			
			Proceed to carry out mining activities	x		
			Display Status of Machine as Running			
1.3.1	1.3.5	Operator on Standby - due to No place to mine OR Waiting for another machine, OR Waiting for Mining Services like water/power	Switch off machine, and	x		
			Alert Dispatch Office, and	x		
			Alert Mine Captain and Production Manager	x		
			Display Equipment Status as Stand-By			
			Display Downtime Information, and			x
			Display Lost Production Hours			
			Mine Captain gives Control instruction to re-arrange production		x	
1.3.1	1.3.4	Equipment Operational Malfunction, e.g. broken shank on Rigs, no fuel, etc.	Switch off machine, and	x		
			Alert Dispatch Office, and	x		
			Alert Mine Captain and Production Manager	x		
			Display Downtime Information, and			x
			Display Lost Production Hours		x	
			Mine Captain gives Control instruction to re-arrange production		x	
1.3.4	1.3.1	Delay Resolved and Machine Released to Production	Proceed to carry out mining activities	x		
			Alert Mine Captain and Production Manager	x		
			Change Equipment Status to Running			
1.3.1	1.3.2	Machine carrying out Non-productive work, e.g. grading roadways using LHDs, carrying materials, etc.	Carry-out non productive work	x		
			Alert Dispatch Office, and	x		
			Alert Mine Captain and Production Manager	x		
			Display Non-productive time Information			x
1.3.2	1.3.1	Work finished	Alert Dispatch Office, and	x		
			Alert Mine Captain and Production Manager	x		
			Display Status of Machine as End of Work			x
1.3.5	1.4.1	Work finished	Alert Dispatch Office, and	x		
			Alert Mine Captain and Production Manager	x		
			Display Status of Machine as End of Work			x
1.4.1	1.1.1	End of Shift or Work Finished	Switch off Machine, and	x		
			End of Shift Checks and Refueling	x		
			Alert Dispatch Office, and	x		
			Alert Mine Captain and Production Manager	x		
			Display Status of Machine as End of Shift			x

C.4. State Transition Charts for Equipment Maintenance Processes

State Transition List - EQUIPMENT REPAIRS AND MAINTANANCE				Current Functional Roles		
Original State	Destination State	Condition	Action	Mechanic Role	Supervisor Role	Contol & Information Role (Manual)
4.2.1	4.2.2	Equipment on Scheduled Planned Maintenance	Print PM Schedule Workorders/Job-Card			
			Avail Service Kits and Oils/Lubricants		x	
			Carry-out Maintenance as per Job-Card	x		
			Display Equipment Status as "On-Maintenance"			
			Generate an Equipment Status Report			x
4.2.2	4.2.1	Planned Preventative Maintenance Completed	Release machine to Dispatch office		x	
			Record Information on CMMS WorkOrder/Job-Card	x		
			Display Equipment Status in Dispatch Office "Standby"			
			Alert Engineer and Equipment Foreman			
			Generate an Equipment Status Report			x
4.2.1	4.2.3	Start of Shift (SOS)	Artisans/Mechanics carries out Statutory Pre-Shift Equipment Checks	x		
			Record Information on CMMS WorkOrder/Job-Card	x		
			Display Equipment Status in Dispatch Office			
			Alert Engineer and Equipment Foreman			x
			Generate an Equipment Status Report			x
4.2.3	4.2.4	Machine in Good Condition to Use	Release machine to Operations	x	x	
			Display Equipment Health Status During Running			
			Alert Engineer and Equipment Foreman			
			Generate an Equipment Status Report			
4.2.3	4.2.5	Defects Identified to be fixed immediately	Switch off machine	x		
			Alert Engineer and Equipment Foreman	x		
			Alert Mine Captain and Production Manager			x
			Display Equipment Status as "Down"			
			Generate an Equipment Status Report			
4.2.4	4.2.1	End of Shift OR Machine is on Standby/Awaiting Operations	Switch off machine	x		
			Alert Engineer and Equipment Foreman	x		
			Alert Mine Captain and Production Manager	x		
			Display Equipment Status as "Off - End of Shift"			
			Generate an Equipment Status Report			
4.2.4	4.2.5	Equipment Malfunction or Breakdown	Switch off machine	x		
			Alert Dispatch Office, Mine Captain and Production Mgr	x		
			Alert Engineering office, Foreman and Engineer	x		
			Log down Equipment and Display Status as "Breakdown"			x
			Track down Downtime hours and Display lost production hrs			
4.2.5	4.2.4	Malfunction or Breakdown Resolved	Alert Dispatch Office, Mine Captain and Production Manager			x
			Alert Engineering office, Foreman and Engineer	x		
			Release Machine back to Operations	x		
			Log-up machine and Display Status as "Running"			
			Display total lost production and hrs			
4.2.5	4.2.6	Major Repairs required	Take machine to workshops	x		
			Carry-out full assessment of repairs required	x		
			Seek approval and Order required Spares		x	
			Carry-out Repairs as required		x	
			Display Major Repairs/Rebuild Plan and Status		x	
			Display Equipment status as "Major Repairs/Rebuild"			
4.2.6	4.2.1	Major Repairs/Rebuild Completed	Hand-over machine to Dispatch office		x	
			Display Equipment Status as "Available"			

D. Chapter 7 Appendices

D.1. Improved State Transition List – Operating equipment

State Transition List - OPERATING EQUIPMENT				Current Functional Roles			Functional Roles with Decision Support System		
Original State	Destination State	Condition	Action	Operator Role	Supervisor Role	Contol & Information Role (Manual)	Operator Role	Supervisor Role	Decision Support System (Computerized)
4.1.1	4.1.2	Start of Shift & Employees Arrive at work	Employees go to Changehouse and proceed to Lamproom	X			X		X
4.1.2	4.1.3	Employee Clocked In	Employees Collect Cap-lamps & rescue packs	X			X		X
			Employees Waiting for Cage	X			X		X
			Employees proceed to waiting place	X			X		X
			Generate Report and Alert Mine Captain and Production Manager on Employees Status		X			X	X
4.1.3	4.1.4	Operator Available	Toolbox Safety meeting		X			X	
			Allocate machines to Operators and work areas		X			X	
			Proceed to Garage and carry out pre-shift checks		X			X	
			Display Equipment Health Status						X
4.1.4	4.1.5	Equipment Mechanically OK and Refuelled	Travel to Working areas	X			X		
4.1.5	4.1.6	Mining areas ready	Proceed to carry out mining activities	X			X		
4.1.6	4.1.7	Equipment Breakdown Occurred	Switch off Machine, and	X			X		
			Alert Dispatch Office, and	X			X		X
			Alert Mine Captain and Production Manager	X			X		X
			Alert Engineering Office			X			X
			Log Down Machine and Display Downtime Information			X			X
			Display Equipment Status as Breakdown						X
			Display/Track Lost Production Hours						X
			Mine Captain gives instruction to re-arrange production		X			X	
4.1.7	4.1.6	Breakdown Resolved	Hand-over machine to Operations						X
			Proceed to carry out mining activities	X			X		
			Display Status of Machine as Running						X
4.1.6	4.1.8	Operator on Standby - due to No place to mine OR Waiting for another machine, OR Waiting for Mining Services like water/power	Switch off machine, and	X			X		
			Alert Dispatch Office, and	X			X		X
			Alert Mine Captain and Production Manager	X			X		X
			Display Equipment Status as Stand-By						X
			Display Downtime Information, and			X			X
			Display Lost Production Hours						X
			Mine Captain gives Control instruction to re-arrange production		X			X	X
4.1.6	4.1.9	Equipment Operational Malfunction, e.g. broken shank on Rigs, no fuel, etc.	Switch off machine, and	X			X		X
			Alert Dispatch Office, and	X			X		X
			Alert Mine Captain and Production Manager	X			X		X
			Display Downtime Information, and			X			X
			Display Lost Production Hours		X			X	
			Mine Captain gives Control instruction to re-arrange production		X			X	
4.1.9	4.1.6	Delay Resolved and Machine Released to Production	Proceed to carry out mining activities	X			X		
			Alert Mine Captain and Production Manager	X			X		
			Change Equipment Status to Running						X
4.1.6	4.1.10	Machine carrying out Non-productive work, e.g. grading roadways using LHDs, carrying materials, etc.	Carry-out non productive work	X			X		
			Alert Dispatch Office, and	X			X		X
			Alert Mine Captain and Production Manager	X			X		X
			Display Non-productive time Information			X			X
4.1.6	4.1.11	Work finished	Alert Dispatch Office, and	X			X		X
			Alert Mine Captain and Production Manager	X			X		X
			Display Status of Machine as End of Work			X			X
4.1.8	4.1.11	Work finished	Alert Dispatch Office, and	X			X		X
			Alert Mine Captain and Production Manager	X			X		X
			Display Status of Machine as End of Work			X			X
4.1.11	4.1.1	End of Shift or Work Finished	Switch off Machine, and	X			X		
			End of Shift Checks and Refueling	X			X		
			Alert Dispatch Office, and	X			X		X
			Alert Mine Captain and Production Manager	X			X		X
			Display Status of Machine as End of Shift			X			X

D.2. Improved State Transition List for Equipment Maintenance

State Transition List - EQUIPMENT REPAIRS AND MAINTANANCE				Current Functional Roles			Functional Roles with Decision Support System		
Original State	Destination State	Condition	Action	Mechanic Role	Supervisor Role	Contol & Information Role	Mechanic Role	Supervisor Role	Decision Support System (Computerized)
4.2.1	4.2.2	Equipment on Scheduled Planned Maintenance	Print PM Schedule Workorders/Job-Card			X			X
			Avail Service Kits and Oils/Lubricants		X			X	
			Carry-out Maintenance as per Job-Card	X			X		
			Display Equipment Status as "On-Maintenance"						X
			Generate an Equipment Status Report			X			X
4.2.2	4.2.1	Planned Preventative Maintenance Completed	Release machine to Dispatch office		X			X	
			Record Information on CMMS WorkOrder/Job-Card	X			X		
			"Standby"						X
			Alert Engineer and Equipment Foreman						X
			Generate an Equipment Status Report			X			X
4.2.1	4.2.3	Start of Shift (SOS)	Artisans/Mechanics carries out Statutory Pre-Shift Equipment Checks	X			X		
			Record Information on CMMS WorkOrder/Job-Card	X			X		X
			Display Equipment Status in Dispatch Office						X
			Alert Engineer and Equipment Foreman			X			X
			Generate an Equipment Status Report			X			X
4.2.3	4.2.4	Machine in Good Condition to Use	Release machine to Operations	X	X		X	X	
			Display Equipment Health Status During Running						X
			Alert Engineer and Equipment Foreman						X
			Generate an Equipment Status Report						X
4.2.3	4.2.5	Defects Identified to be fixed immediately	Switch off machine	X			X		
			Alert Engineer and Equipment Foreman	X			X		X
			Alert Mine Captain and Production Manager			X			X
			Display Equipment Status as "Down"						X
			Generate an Equipment Status Report						X
4.2.4	4.2.1	Operations	Switch off machine	X			X		
			Alert Engineer and Equipment Foreman	X			X		X
			Alert Mine Captain and Production Manager	X			X		X
			Display Equipment Status as "Off - End of Shift"						X
			Generate an Equipment Status Report						X
4.2.4	4.2.5	Equipment Malfunction or Breakdown	Switch off machine	X			X		
			Alert Dispatch Office, Mine Captain and Production Mgr	X			X		
			Alert Engineering office, Foreman and Engineer	X			X		
			Log down Equipment and Display Status as "Breakdown"			X			X
			Track down Downtime hours and Display lost production hrs						X
4.2.5	4.2.4	Malfunction or Breakdown Resolved	Alert Dispatch Office, Mine Captain and Production Manager			X			X
			Alert Engineering office, Foreman and Engineer	X			X		X
			Release Machine back to Operations	X			X		
			Log-up machine and Display Status as "Running"						X
			Display total lost production and hrs						X
4.2.5	4.2.6	Major Repairs required	Take machine to workshops	X			X		
			Carry-out full assessment of repairs required	X			X		
			Seek approval and Order required Spares		X			X	
			Carry-out Repairs as required		X			X	
			Display Major Repairs/Rebuild Plan and Status		X				X
			Display Equipment status as "Major Repairs/Rebuild"						X
4.2.6	4.2.1	Major Repairs/Rebuild Completed	Hand-over machine to Dispatch office		X			X	X
			Display Equipment Status as "Available"						X

D.3. Improved Equipment Maintenance – Value adding and Non-Value Adding Activities

State List/Process SPECIFICATION - EQUIPMENT REPAIR & MAINTENANCE PROCESSES				Current Duration of State in Hours			Value added through Real-Time Decision Support			
	No	State	Description	Value Adding (VA)	Non-VA Necessary	Non-VA Unneccessary	Value Adding (VA)	Non-VA Necessary	Non-VA Unneccessary	
Start of Shift (SOS) Activities	4.2.1	Equipment Off	Equipment may be in the Off state due to end of shift, machine on standby, machine on breakdown, or machine requiring major repairs and overhauls/rebuilds.		1.13			1.13		
	4.2.2	Pre-Shift Equipment Checks & Inspections	Before a machine is released out for production, Statutory Pre-Shift equipment checks and Inspectiond must be carried out by the mechanics/artisans. A daily maintenance checklist on the CMMS must be filled in by artisan. Statutory checks like brake tests, and safety machine interlocks are inspected		0.45			0.45		
In-Shift Operations	4.2.3	Machine in Proper Operating Condition	After machine is inspected by mechanics, it is certified to be OK and is released for production. The machine is now in a state of use by operations.	18.69			19.59			
	4.2.4	Corrective Maintenance (Emergency Repairs & Breakdowns)	This state arises from two conditions. It could be that defects are identified during pre-shift inspections and they are then immediately attended to and fixed. Corrective work also happens when during operation and the machine breaksdown down and has to be fixed. Some of the breakdowns are major and need overhauls and they will take more than a shift work.			2.27			1.37	*Reduce Delays due to Reporting of Breakdowns*
	4.2.5	Planned Preventitive Maintenance (PM Services & Planned Repairs)	Here Scheduled maintenance work is carried as planned on the PM Schedule. Maintenance service kits have to be made available for the work to commence. All work carried out must be recorded on the PM CMMS Work Orders.		1.46			1.46		
	4.2.6	Major Repairs (Large Repairs, Overhauls & Rebuilds)	Major repairs, overhauls and rebuilds will require more than a shift's work. Some of these repairs are planned but others are a result of damages that may have occurred to the equipment.							
				18.69	3.04	2.27	19.59	3.04	1.37	
			% of Total	78%	13%	9%	82%	13%	6%	

D.4. Improved In-Shit Control – Value Adding and Non-Value Adding Activities

State List/Process Specification - MANAGE AND CONTROL OPERATIONS DURING SHIFT				Current Duration of State in Hours			Value added through Real-Time Decision Support			
	No	State	Description	Value Adding (VA)	Non-VA Necessary	Non-VA Unneccessary	Value Adding (VA)	Non-VA Necessary	Non-VA Unneccessary	
In-Shift Operations	4.4.1	Equipment Off	During A shift, a machine maybe off due to a couple of reasons which include: End of Work, Operator gone to report a problem on the machine, due to Secondary Blasting, due to the operator not at work or due to Machine coming from a Breakdown State.		2.33			2.33		
	4.4.2	Equipment on Standby	Equipment/Machine can be on Standby due to : Machine waiting to be allocated place of work, can be a Dumptruck waiting for an LHD, or an LHD waiting for a Dumptruck, Installing Mining Services especially for drills, Making place safe like barring down, or place could have been stopped due to poor mining conditions such as ventilation, fissure water or gases.			4.45			2.23	*Reduce Standing time by 50% adding to effective time*
	4.4.3	Equipment Mining	Equipment performing the Required Mining Function such as Drilling, Loading or Hauling. In this case all the required equipment is available, the working areas are made safe and all the services have been installed such as water and ventilation.	11.13			16.03			
	4.4.4	Process Malfunction / Delays	A Process delay or malfunction can occur such as finished diesel, no drill bits, or shanks, or failed ventilation pipes, or water pipes failure			3.82			1.15	*Eliminate delays by 70% through visibility*
	4.4.5	Diagnosing & Fixing Equipment Problem	An Equipment Breakdown would have occurred and the Technicians and Engineering personnel will be busy diagnozing and fixing the problems			2.27			2.27	
				11.13	2.33	10.54	16.03	2.33	5.64	
			% of Total Time	46%	10%	44%	67%	10%	24%	

D.5. Potential Improvements at MineABC due to Technical Interventions

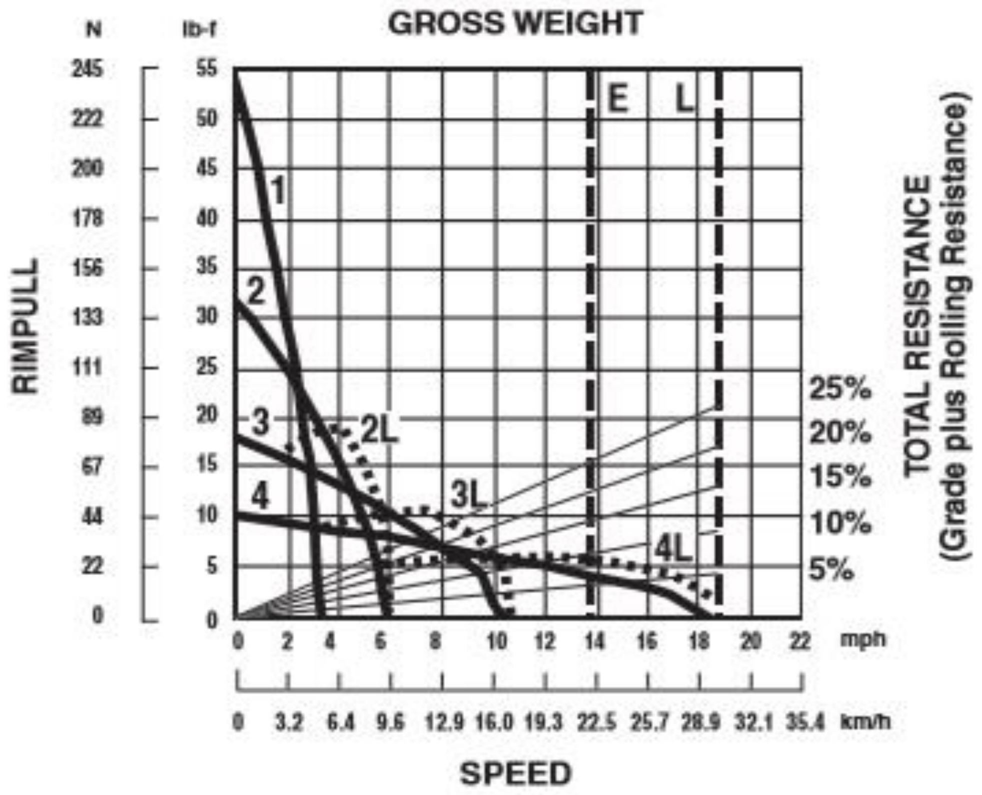
Production Capacity and Improvement Potential Chart

	Level Factor	Description	Notes	Cycle time	Loader Throughput (Loads/Hr)	Total Throughput (tons/hr)	Effective Operating time (Hrs/Day)	Daily Tonnage	Monthly tonnage (26 days/Month)	Annual tonnage
Available Capacity	System Factors	Hoisting Capacity	Winders had capacity to hoist all from underground			816	18	14,696	382,096	4,585,152
	System Factors	Total possible capacity LHDs	23 Loaders x @ 6.5 tons fill factor, based on 200m tramming distance at speed of 9.6 km/hr loaded and load & dump time of 8 minutes	10.5	5.7	854	14	11,960	310,960.00	3,731,520
Current Capacity	System Factors	Current LHD production rate	Currently loaders only doing 3.2 loads/hr @ 32% utilization	17.6	3.4	699	8.9	6,221	161,742.00	1,940,904
Improved Capacity	System Factors	System lead time improvement	Improve ore residence time from 7.95 days to 5.31 days and adds 1,414 tons/day.					1,414	36,764.00	441,168
	System Factors	Gross cycle time improvements	Improve gross cycle time from 437 sec/ton to TAKT time of 266 sec /ton			287	7.7	2,201	57,223.96	686,687
	Workstation losses	Cycle time losses	Net cycle time is an equipment capability and tramming distance., improved from 3.4 to 6.5 loads/hr therefore an additional 3.1 loads/hr per LHD	9.23	3.1	463	7.7	3,559	92,541.70	1,110,500
	Workstation losses	Reliability factors	Improve MTBF from15.82 minutes to 27.12 minutes improves the loads/hr to 8.1 versus 6.5	7.41	1.6	239	7.7	1,842	47,887.84	574,654
	Workstation losses	Maintainability factors	Reduce MTBF from 6.8 to 4.29	12.00	0.8	120	7.7	921	23,943.92	287,327
	Workstation losses	Utilized hours	Improved through monitoring of value adding and non-value adding processes. Total running time improved	17.6	3.4	510	4.6	2,364	61,452.16	737,426
						Total Potential Improvements		**12,301**	**319,813.57**	**3,837,763**

D.6. CAT R1600G Gradeability/Rimpull Chart (Source – CAT Performance Handbook Edition 40 (2010))

R1600G Rimpull-Speed-Gradeability
● 18x25 Tires

Underground Mining

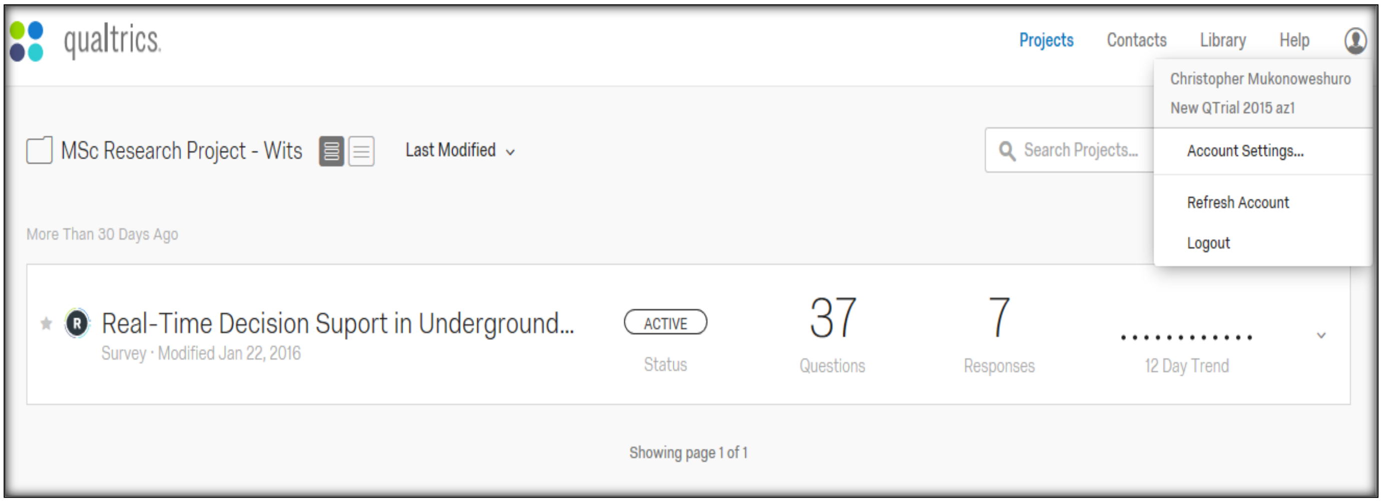


KEY
1 — 1st Gear
2 — 2nd Gear
3 — 3rd Gear
4 — 4th Gear

KEY
E — Empty 29 800 kg (65,698 lb)
L — Loaded 40 000 kg (88,185 lb)

E. On-line Survey Questionnaire and Sample Responses

(Qualtrics Survey Engine Used - https://newqtrial2015az1.az1.qualtrics.com)



MSc Research Project - Wits

More Than 30 Days Ago

Real-Time Decision Suport in Underground...
Survey · Modified Jan 22, 2016

ACTIVE
Status

37
Questions

7
Responses

12 Day Trend

Showing page 1 of 1

On-Line Survey Questions
Decision Support Systems for Underground Mining

Section A – Mining Systems and Fleet Productivity

Q1 Indicate Type of Mineral(s) Mined
Q2 Mine's Budget Annual Ore Output (Metric tons per year) ______________________________
Q3 Types of Mining Method(s) Employed
Q4 Daily Production target output (metric tons/day) _____________________________________

Q5 Mining Access and Ore Transportation from the mine
☐ Vertical Shaft (1)
☐ Ramp/Decline (2)

*Q6 Total Number of Employees - Underground mining*________________________________
Q7 LHD Capacity in Metric Tons vs Number of LHDs in the mine
Q8 Dumptrucks Capacity in Metric Tons vs Number of Trucks in the mine
Q9 Average LHD Availability ____ %
Q10 Average LHD Utilization (Use of Available time) _________________________ %
Q11 Average Dump-truck Availability __________________________________ %
Q12 Average Dump-truck Utilization (Use of Available time) _______________________ %
Q13 Average Drill Rig Availability __________________________________ %
Q14 Average Drill Utilization (Percussion Hours) ______________________________ %
Q15 Average Equipment Reliability Data for Trackless Fleet (in Hours)

Q16 Trackless Equipment (load & haul) Productivity

Q17 Drill Rigs Productivity

Section B - Decision Support Systems

Q18 ERP System is used at the Mine (SAP, MIMS, DELTA ERP, etc) _______________
Q19 Is there an Operations Execution System or Operations Management Software in Place - which integrates Mine Planning and Operations (MineOPs, RPM EXACT for Enterprises, etc) ?

Q20 Is there a Visual Mine Operations Control Centre – (Control Room) For Real-Time monitoring and tracking of operations underground?

Q21 When was a Mine Operations Control Room / Mission Control Centre Installed__________
Q22 What was the Production Improvement in terms of Tons mined after installation of the Mine Operations Control Centre_______________________________ %

Q23 Is there a Proper Dispatch Office Underground with a Senior Official In-Charge (Shift-boss, MIC, Mine-Captain or Engineer)

Q24 Is there a Computerized Equipment Dispatch System in place with Real-Time Monitoring Capabilities?

Q25 When was an Computerized Equipment Dispatch System Installed? __________________
Q26 What was the Production Improvement in terms of Tons mined after installation of the Computerized Dispatch System? _____________________________________ %

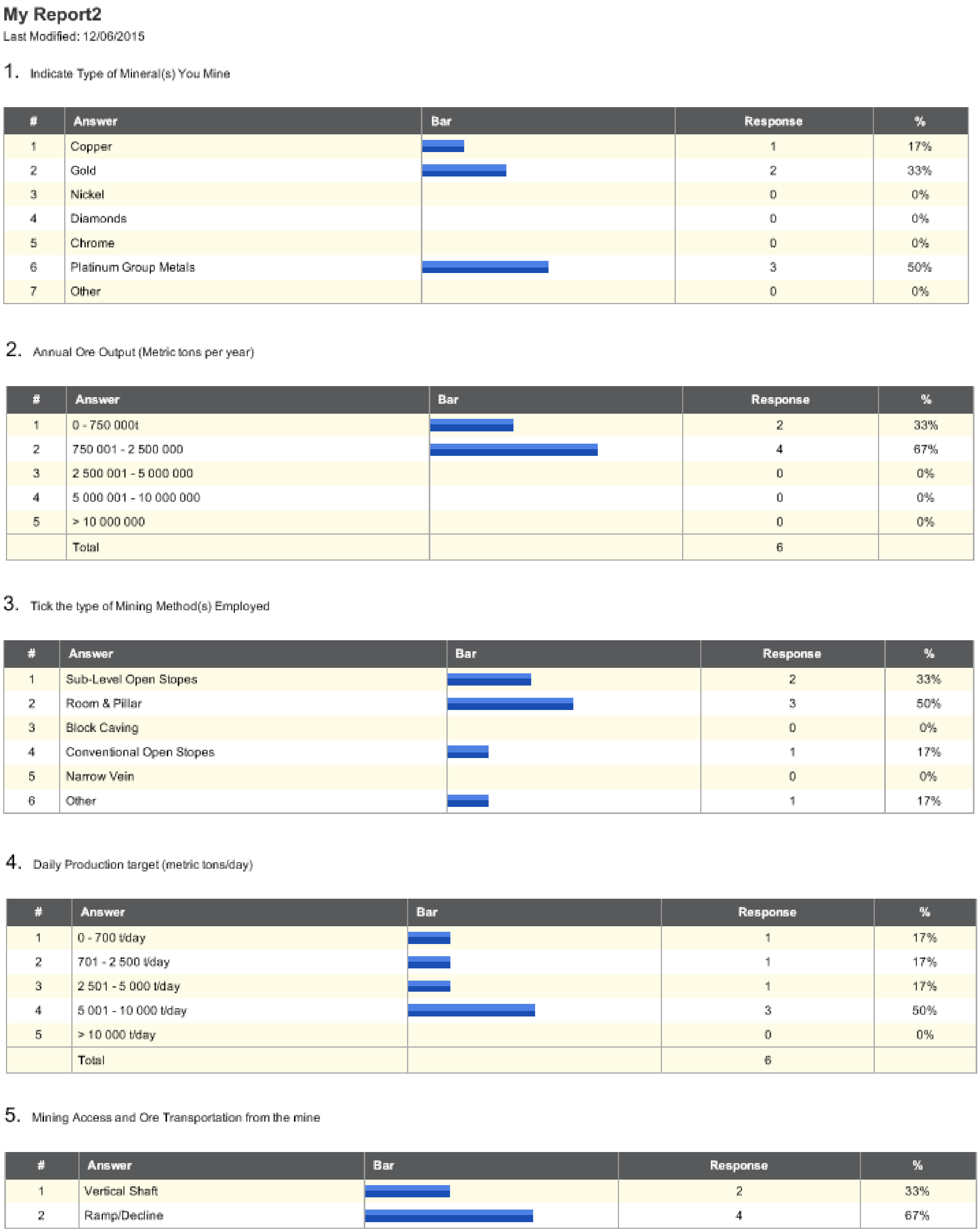
Q27 Does the mine have any of the following Technologies in the Underground Mine
Q28 Types of Communication Backbones in Use at the mine
Q29 Type(s) of Shift Structure in the underground mine
Q30 Type of Systems available (Manual or Computer System) for Supervisory Control of each of the listed activities below before, during and after the shift

Q31 Type of Systems available (Manual or Computer System) for Monitoring listed activities below before, during and after the shift

Q32 Indication of current mining system delays per type of machine:
Q33 Average Hauling Distance for Dump-trucks from Loading Ramp to Tips (in KM) ___
Q34 Average Tyre Life for Production Trackless Fleet (LHD & Dumptrucks) in Hours __
Q36 Level of Automation on Mining Equipment
Q37 Current Actual Total Production Ore tons vs. Budget Ore tons for the Past Year to Date (Compliance to production Budget) _________________________________ %

Q35 Brands and No off - of Trackless Equipment in the underground fleet

Some of the NOTABLE RESPONSES FROM ON-LINE SURVEY



My Report2

Last Modified: 12/06/2015

1. Indicate Type of Mineral(s) You Mine

#	Answer	Bar	Response	%
1	Copper	▬	1	17%
2	Gold	▬	2	33%
3	Nickel		0	0%
4	Diamonds		0	0%
5	Chrome		0	0%
6	Platinum Group Metals	▬	3	50%
7	Other		0	0%

2. Annual Ore Output (Metric tons per year)

#	Answer	Bar	Response	%
1	0 - 750 000t	▬	2	33%
2	750 001 - 2 500 000	▬	4	67%
3	2 500 001 - 5 000 000		0	0%
4	5 000 001 - 10 000 000		0	0%
5	> 10 000 000		0	0%
	Total		6	

3. Tick the type of Mining Method(s) Employed

#	Answer	Bar	Response	%
1	Sub-Level Open Stopes	▬	2	33%
2	Room & Pillar	▬	3	50%
3	Block Caving		0	0%
4	Conventional Open Stopes	▬	1	17%
5	Narrow Vein		0	0%
6	Other	▬	1	17%

4. Daily Production target (metric tons/day)

#	Answer	Bar	Response	%
1	0 - 700 t/day	▬	1	17%
2	701 - 2 500 t/day	▬	1	17%
3	2 501 - 5 000 t/day	▬	1	17%
4	5 001 - 10 000 t/day	▬	3	50%
5	> 10 000 t/day		0	0%
	Total		6	

5. Mining Access and Ore Transportation from the mine

#	Answer	Bar	Response	%
1	Vertical Shaft	▬	2	33%
2	Ramp/Decline	▬	4	67%

6. Total Number of Employees Directly Under Mining/Ore Production Division at Mine

#	Answer	Bar	Response	%
1	0 - 500		2	33%
2	501 - 1 500		3	50%
3	1 501 - 2 500		1	17%
4	2 501 - 4 000		0	0%
5	> 4000		0	0%
	Total		6	

7. Please Indicate your LHD Capacity in Metric Tons vsTotal Number of LHDs (vertical is LHD Capacity and Horizontal is No of LHDs in the mine)

#	Question	0 - 7 LHDs	8 - 15 LHDs	16 - 23 LHDs	24 - 31 LHDs	More than 35 LHDs	Total Responses	Mean
1	0 - 2.5 t	2	0	0	0	0	2	1.00
2	2.6 t - 6.5 t	1	0	1	0	0	2	2.00
3	6.6 t - 9.0 t	0	1	0	0	0	1	2.00
4	9.1 t - 15 t	2	1	0	0	0	3	1.33
5	16 t - 20t	0	0	0	1	0	1	4.00
6	> 20 ton	0	0	0	0	0	0	0.00

8. Please Indicate your Dumptrucks Capacity in Metric Tons vsTotal Number of Trucks(vertical is Truck Capacity and Horizontal is No of Trucks in the mine)

#	Question	0 - 7 LHDs	8 - 15 LHDs	16 - 23 LHDs	24 - 31 LHDs	More than 35 LHDs	Total Responses	Mean
1	0 - 10 t	0	0	0	0	0	0	0.00
2	11 t - 15 t	0	0	0	0	0	0	0.00
3	16 t - 20 t	0	0	0	0	0	0	0.00
4	21 t - 30 t	0	3	0	0	0	3	2.00
5	31 ton - 40 t	0	1	0	0	0	1	2.00
6	41 t - 50 t	1	0	0	0	0	1	1.00
7	51 - 60 t	0	0	0	0	0	0	0.00
8	> 60 t	0	0	0	0	0	0	0.00

9. Average LHD Availability

#	Answer	Bar	Response	%
1	0 - 50%		1	17%
2	51% - 65%		0	0%
3	66 % - 75 %		1	17%
4	76 % - 85 %		2	33%
5	> 85%		2	33%
	Total		6	

10. Average LHD Utilization (Use of Availability)

#	Answer	Bar	Response	%
1	0 - 30%		1	17%
2	31% - 55%		1	17%
3	56% - 65%		2	33%
4	66% - 75%		1	17%
5	>75%		1	17%
	Total		6	

11. Average Dumptruck Availability

#	Answer	Bar	Response	%
1	0 - 50%		1	20%
2	51% - 65%		0	0%
3	66% - 75%		2	40%
4	76% - 85%		1	20%
5	>85%		1	20%
	Total		5	

12. Average Dumptruck Utilization (Use of Availability)

#	Answer	Bar	Response	%
1	0 - 30%		1	20%
2	31% - 55%		1	20%
3	56% - 65%		2	40%
4	66% - 75%		1	20%
5	>75%		0	0%
	Total		5	

13. Average Drill Rig Availability

#	Answer	Bar	Response	%
1	0 - 50%		1	17%
2	51% - 65%		0	0%
3	66% - 75%		0	0%
4	76% - 85%		1	17%
5	>85%		4	67%
	Total		6	

14. Average Drill Utilization (Percussion)

#	Answer	Bar	Response	%
1	0 - 30%		1	20%
2	31% - 55%		4	80%
3	56% - 65%		0	0%
4	66% - 75%		0	0%
5	>75%		0	0%
	Total		5	

15. Enter Average Equipment Reliability Data Below for your Trackless Fleet (in Hours)

Default - LHDs	
MTBF (Mean Time Between Failures)	**MTTR (Mean Time to Repair)**
30	8
20	2
27	3.2
25	4
6	2

16. Please Enter your current average Trackless Equipment Productivity

Default - LHDs		
Buckets/Hr or Trips/Hr	**Tons/Hr**	**Tons/Shift**
12	65	420
37	300	1800
7	56	220
	22	
		700
Default - Dumptrucks		
Buckets/Hr or Trips/Hr	**Tons/Hr**	**Tons/Shift**
3	60	400
8	150	900
1	22	88
		350

19. Do you have an Operations Execution System / Operations Management Software in Place - which integrates Mine Planning and Operations (MineOPs, RPM EXACT for Enterprises, etc) ?

#	Answer	Bar	Response	%
1	Yes		1	20%
2	No		4	80%
	Total		5	

20. Do you have a Mine Operations Control Centre -Mission Control Centre /Control Room For Real-Time monitoring and tracking of operations underground?

#	Answer	Bar	Response	%
1	Yes		2	40%
2	No		3	60%
	Total		5	

21. When was a Mine Operations Control Room / Mission Control Centre Installed

#	Answer	Bar	Response	%
1	> 20 years ago		0	0%
2	10 years ago		0	0%
3	5 years ago		0	0%
4	3 years ago		0	0%
5	1 year ago		2	40%
6	None		3	60%
	Total		5	

23. Do you have a Proper Dispatch Office Underground with a Senior Official In-Charge (Shift-boss, MIC, Mine-Captain or Engineer)

#	Answer	Bar	Response	%
1	Yes		2	40%
2	No		3	60%
	Total		5	

24. Do you have a Computerized Equipment Dispatch System in place with Real-Time Monitoring Capabilities?

#	Answer	Bar	Response	%
1	Yes		1	20%
2	No		4	80%
	Total		5	

25. When was an Equipment Dispatch System Installed?

#	Answer	Bar	Response	%
1	20 years ago		1	20%
2	10 years ago		0	0%
3	5 years ago		0	0%
4	3 years ago		0	0%
5	1 year ago		1	20%
6	None		3	60%
	Total		5	

26. What was the Production Improvement in terms of Tons mined after installation of the Dispatch System?

#	Answer	Bar	Response	%
1			0	0%
2	5%		1	100%
3	10%		0	0%
4	20%		0	0%
5	>30%		0	0%
	Total		1	

27. Do you have any of the following Technologies in your Underground Mine

#	Question	Yes	No	Total Responses	Mean
1	Equipment Locating system/RFID Tagging	1	4	5	1.80
2	Computerized Employee Clocking System	4	1	5	1.20
3	Computerized Lamp-room Control System	3	2	5	1.40
4	Underground Employee locating system /Cap-lamp tagging	1	4	5	1.80
5	Collision avoidance system	3	2	5	1.40
6	Line of Site Remote Systems for LHDs, Rigs or Trucks	3	2	5	1.40
7	Fully Autonomous Mining System with Surface Control Room	0	5	5	2.00
8	Computerized Underground Control-Rooms	0	5	5	2.00
9	Equipment Health & Real-Time Status Monitoring System	1	4	5	1.80
10	Integrated Fuel & Fleet Management System	1	4	5	1.80
11	Are all the above systems integrated ? (not stand-alone systems)	1	4	5	1.80

28. Tick Types of Communication Backbones in Use at your mine

#	Question	Yes	No	Total Responses	Mean
1	Hard-wired Telephone System	4	0	4	1.00
2	Leaky Feeder System	3	2	5	1.40
3	Ethernet	3	1	4	1.25
4	Fibre-Optic	3	1	4	1.25
5	Wi-Fi	4	0	4	1.00
6	WLAN	4	0	4	1.00
7	Other	0	0	0	0.00

29. Mark the type(s) of Shift Structure in your mine

#	Answer	Bar	Response	%
1	6-Days Week		0	0%
2	CONTOPS		1	20%
3	2 x 8hr		0	0%
4	2 x 10hr		2	40%
5	2 x 12 hr		0	0%
6	3 x 8 hr		1	20%
7	3 x 7hr		0	0%
8	Other		1	20%

30. Please Mark all the type of Systems available (Manual or Computer System) for Supervisory Control of each of the listed activities below before, during and after the shift

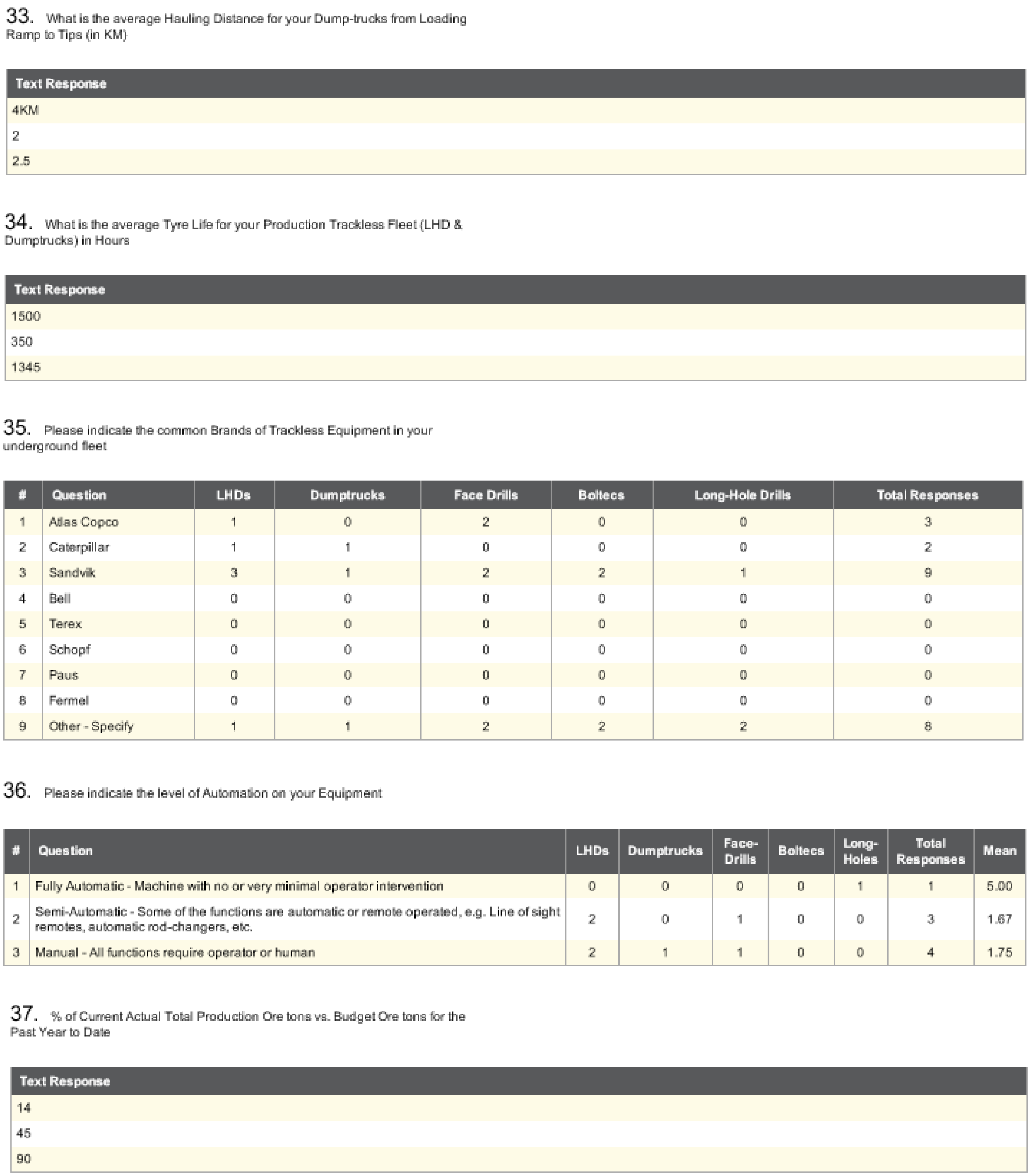
#	Question	Manual Paperwork (Including Log-Books)	Computerized (ERP/MES/SAP)	Real-Time (Visible as event happens)	Verbal Reporting btn Supervisors	Radios / walkie talkies	Phone	Video	Internet / Web-Based	Total Responses
1	How do you know the Status of Equipment Start of Shift?	4	0	1	4	1	2	0	0	12
2	How do you know the Status of Working areas Start of Shift?	5	0	0	3	1	1	0	0	10
3	How do you know the number of Employees Start of Shift?	3	1	0	1	0	0	0	0	5
4	What is your System for Dispatch of Equipment?	4	0	0	3	1	1	0	0	9
5	How do you know the Status of Production after the shift?	4	0	0	2	0	2	0	1	9
6	Your system for Stoppages and Breakdown Reporting?	4	0	0	3	2	2	0	1	12

31. Please Also Mark all the type of Systems available (Manual or Computer System) for Monitoring listed activities below before, during and after the shift

#	Question	Manual Paperwork (Including Log-Books)	Computerized (ERP/MES/SAP)	Real-Time (Visible as event happens)	Verbal Reporting btn Supervisors	Radios / walkie talkies	Phone	Video	Internet / Web-Based	Total Responses
1	System for Monitoring of production status during the shift	4	0	0	4	2	3	0	1	14
2	System for monitoring Status of Production after the shift	5	0	0	3	1	3	0	1	13
3	System for Monitoring of the System Delays during Shift	5	0	0	3	1	2	0	1	12
4	System for monitoring Production Output per machine in a Shift	4	0	0	2	1	2	0	1	10
5	System for monitoring Production Output per mining zone	4	0	0	2	1	2	0	1	10
6	System for Monitoring Ore Grade	4	0	0	2	1	2	0	1	10
7	System for monitoring Crushed tons	4	1	0	2	0	2	0	1	10
8	System for monitoring Hoisted Tons	4	1	0	1	0	2	0	1	9

32. Give an Indication of your system delays per type of machine by filling in the table below

#	Question	Rigs	LHDs	Trucks
1	Average Hours taken for Travelling to working areas in a Shift	0.60	1.55	1.10
2	Average Hours available as effective face/use time in a Shift	3.60	3.20	3.40
3	Average Hours classified as Engineering Delays in a Shift	2.22	6.36	4.22
4	Total Shift Time classified as Production Delays in Hours	1.00	0.80	0.80
5	Time at the Lamp-rooms in minutes	3.03	6.00	6.00
6	Time in minutes for Safety / Toolbox Meetings	8.00	8.00	8.00
7	Time in minutes used for Re-fuelling machines	12.07	12.07	12.07
8	Average Time in minutes for Breakdown Response	11.00	12.00	12.00
9	Unclassified Delays in Hours	0.80	0.80	0.80



33. What is the average Hauling Distance for your Dump-trucks from Loading Ramp to Tips (in KM)

Text Response
4KM
2
2.5

34. What is the average Tyre Life for your Production Trackless Fleet (LHD & Dumptrucks) in Hours

Text Response
1500
350
1345

35. Please indicate the common Brands of Trackless Equipment in your underground fleet

#	Question	LHDs	Dumptrucks	Face Drills	Boltecs	Long-Hole Drills	Total Responses
1	Atlas Copco	1	0	2	0	0	3
2	Caterpillar	1	1	0	0	0	2
3	Sandvik	3	1	2	2	1	9
4	Bell	0	0	0	0	0	0
5	Terex	0	0	0	0	0	0
6	Schopf	0	0	0	0	0	0
7	Paus	0	0	0	0	0	0
8	Fermel	0	0	0	0	0	0
9	Other - Specify	1	1	2	2	2	8

36. Please indicate the level of Automation on your Equipment

#	Question	LHDs	Dumptrucks	Face-Drills	Boltecs	Long-Holes	Total Responses	Mean
1	Fully Automatic - Machine with no or very minimal operator intervention	0	0	0	0	1	1	5.00
2	Semi-Automatic - Some of the functions are automatic or remote operated, e.g. Line of sight remotes, automatic rod-changers, etc.	2	0	1	0	0	3	1.67
3	Manual - All functions require operator or human	2	1	1	0	0	4	1.75

37. % of Current Actual Total Production Ore tons vs. Budget Ore tons for the Past Year to Date

Text Response
14
45
90