Time and spatial tracking of metal content from in-situ to the plant entry: A digital mining technology approach

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DECLARATION

I declare that this thesis is my own, unaided work. Where use has been made of the work of others, it has been duly acknowledged. It is being submitted for the Degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before in any form for any degree or examination in any other University.

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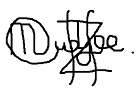

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This 4th day of August 2020

ABSTRACT

Ore and metal accounting and reconciliation processes at most South African mines have been a long-standing challenge. Efficiency factors such as the Mine Call Factor (MCF) have been developed and used to monitor the overall mining and metallurgical processes. The MCF at seven AngloGold Ashanti Mines in South Africa averaged at 70% annually from 2010 to 2017. This implies a 30% loss of gold, equivalent to approximately 1.4 billion rand which is material. Metal losses are categorized as either apparent or real. The focus in this thesis is on investigating digital technologies for measuring, monitoring and tracking physical metal content from underground to surface and reporting in real time in a control room on the surface. The fundamental question in the thesis was to determine if digital technologies are suitable for measuring, monitoring and tracking metal content from underground to surface.

In order to test this concept, a literature review was conducted on various topics that embody metal accounting and reconciliation with a key focus on current and new digital technologies and systems for tracking broken ore variables. These include the MCF theory; theory of volume and in process measurements; material monitoring and tracking technology options for broken ore variables; leading mine planning and reconciliation software options; and Microdots technology as a potential solution for ore tracking.

Following the literature review, a conceptual framework for tracking metal content was developed using a typical underground mechanised mining operation as an example. Technology options for tracking metal content and associated variables in a typical production environment at various stages was developed. These are the in-situ

stage; after blast; ore transportation; tipping into ore bins or passes; and stockpiling on the surface.

An implementation plan was developed for measurement, monitoring and tracking of volume and mass, sampling for grade, fragmentation, density and moisture content as well as location-based information. This implementation process is made up of several steps - including identification of the purpose for the measurement, the system used for that particular measurement, development of a site-specific protocol for each of the equipment and a competency standard. A combined digital mining technology (CDMT) approach for metal tracking from underground to surface was then developed. In the CDMT approach, decisions in terms of the best technology or equipment would have to be made in accordance with the mine's standard operating protocol. A SWOT tool was used to identify the best technology for measurement, monitoring and tracking each of the variables. This thesis demonstrates that material tracking is possible through the application of digital technologies during the production aspect of the mine value chain. Technologies such as the RF tags introduced in the past resulted in the prevention of cross tramming of ore to waste and vice versa. The application of several digital technologies to measure, monitor and track metal content has the ability to distinguish between physical and apparent losses, which is a major step forward in understanding metal loss from mine to mill.

LIST OF ABBREVIATIONS

AC	Autocorrelation Coefficients
ADF	Augmented Dickey-Fuller
AdvOPM	Advanced Open Pit Metals
AdvUGC	Advanced Underground Coal
AdvOCC	Advanced Open Cut Coal System
AE	Analytical Error
AGG	Aggregation
ANOVA	Analysis of Variance
AR	Autoregressive
ARMA	Autoregressive Moving Average
ASD	Auto Slope Design
AVG	Average
BME	Basic Mining Equation
BSD	Berkeley Software Distribution
BS:812	British Standard: 812
CAD	Computer Aided Design
CAS	Chemical Abstract Service
CCOHS	Canadian Centre for Occupational Health and Safety

CDMT	Combined Digital Mining Technology
CIM	Centric Inventory Manager
CMP	Critical Measurement Point
CNS	Central Nervous System
COMRO	Chamber of Mine's Research Organization
CSV	Comma Separated Value
CUSUM	Cumulative Sum
CV	Calorific Value
DBD	Dry Bulk Density
DE	Delimitation Error
DD	Dragline and Dozer Section Designer
DIAT	Digital Image Analysis Technique
DigiMine	Wits DigiMine
EE	Extraction Error
ERP	Enterprise Resource Planning
FSE	Fundamental Sampling Error
F	Cumulative Feed
GCM	Grade Control Model
GED	Generalised Error Distribution

GSE	Group and Segregation Error
GIS	Geographic Information System
GNU	GNU’s
HMS	Heavy Media Separation
HTML	Hypertext Markup Language
JKMRC	Julius Kruttschnitt Mineral Research Centre
JSE	Johannesburg Stock Exchange
IBM	International Business Machine
ID	Identity
IDE	Increment Delimitation Error
IEC	International Electrotechnical Commission
IEE	Increment Extraction Error
IR	Infrared
ISBD	In-Situ Bulk Density
ISO	International Organization for Standardization
Inc.	Incorporated
INE	In-situ Nugget Effect
IP	Internet Protocol
IRS	Intelligent Reconciliation System

IS	Interactive Scheduler
ISO	International Organization for Standardization
IPE	Increment Preparation Error
IWE	Increment Weighing Error
KPSS	Kwiatkowski-Phillips-Schmidt-Shin
LoM	Life-of-Mine
LCD	Liquid Crystal Display
LHD	Load-Haul-Dump
LHS	Landform and Haulage System
LIMS	Laboratory Information Systems
LLC	Limited Liability Company
LTD	Limited Company
MA	Moving Average
MacOS	Macintosh Operating System
MCF	Mine Call Factor
MEK	Methyl Ethyl Ketone
METF	Mining Education Trust Fund
MIK	Multiple Indicator Kriging
MOA	Mined Out Area

MP	Measurement Point
MPTI	Metso Processing Technology Innovation
MRM	Mineral Resource Management
MSDS	Material safety data sheet
MTD	Mine To Date
NCM	New Concept Mining
NFC	Near frequency communication
NIR	Not In Reserve
NLP	Natural language processing
ODS	OpenDocument Spreadsheet
OS	Operating System
PAC	Partial Autocorrelation coefficient
PC	Personal Computer
PCF	Plant call Factor
PDF	Portable Document Format
PE	Preparation Error
PH	Potential of Hydrogen
PIE	Process Integration Error
PP	Phillips-Perron

PPE	Personal Protective Equipment
PTI	Process Technology and Innovation
PTY	Proprietary
RDP	Resource Development Plan
R and R	Resource and Reserve
QAQC	Quality Assurance and Quality Control
R^1	Correlation Coefficient
R^2	Cumulative Reclaim
RF	Radio Frequency
RFID	Radio Frequency Identification
RDP	Resource Development Plan
ROM	Run-of-Mine
RPAS	Remotely Piloted Aircraft Systems
SANS	South African National Standard
SAMREC	South African Code for Reporting of Exploration results Mineral Resources and Mineral Reserves
SD	Standard Deviation
SG	Specific Gravity
SCF	Shaft Call Factor

SLS	SaLt State
SSDML	Sibanye-Stillwater Digimine laboratory
SOP	Standard Operating Procedures
SpatialDB	Spatial Dash Board
SWOT	Strength Weakness Opportunity and Test
TAB	Tablature
TCP	Transmission Control Protocol
TOC	Theory of Constraint
UAV	Unmanned Aerial Vehicles
UBC	University of British Columba
UGDB	Underground Drill and Blast
UN	United Nations
UV	Ultraviolet
USA	United States of America
VCR	Ventersdorp Contact Reef
VIP	Visual Integration Platform
VR	Virtual Reality
WCSB	World’s Conference on Sampling and Blending
WE	Weighing Error

WMI-OFA	Wits Mining Institute Ore Flow Analyser
WW1	World War One
XLSX	Microsoft Excel Open XML Format Spreadsheet File
XLS	Excel Spreadsheet
XLTS	Excel Open XML Spreadsheet Template File
Xn	Harmful
XRF	X-ray Fluorescent
1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional

LIST OF PUBLICATIONS

The publication listed below have emanated from this thesis:

1. Tetteh, M.N.M and Cawood, F.T (2017), Design considerations for accurate coal measurements points: Towards accurate reconciliation for integrated mine planning, Journal of the Southern African Institute of Mining and Metallurgy, Volume 117.

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The opinions expressed in this thesis are those of the author and may not necessarily represent the policies of the companies and institutions mentioned in this thesis.

DEDICATION

This thesis is dedicated to God Almighty and to my family and friends for their support throughout my life.

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1 Introduction

1.1 Chapter overview

The Mine Call Factor (MCF) theory, as described by Storrar (1981), is generally used in underground mining to determine the effectiveness (expressed in percentages) of all the processes and measurement systems in the mining value chain; from the mineral product evaluation stage up to final product. There are several technical disciplines that cut across this subject area, making it difficult to investigate and determine where actual problem areas are on a particular mine. A typical example is when reconciling planned quality, quantity and time estimates with actual measurements, from the various measurement systems, most noticeably when these measurements are outside tolerable levels.

This research is impelled by the outcome of the author's M.Sc. research report on MCF issues (Tetteh, 2014). The following are key findings in the research:

- A need to address MCF issues from a technology perspective focusing on identifying possible physical metal losses – for example, the use of sensors such as radio frequency identification tags and readers to track ore parcels from their respective sources throughout the process;
- Mines working from similar geological orebodies could work towards an integrated standardized protocol for mass measurements, sampling, sample preparation and analysis from the mining face to run-of-mine (ROM);
- The need to conduct mine to mill reconciliations following the generic model (Figure 1.1), to avoid disconnections between measuring points when doing reconciliations.

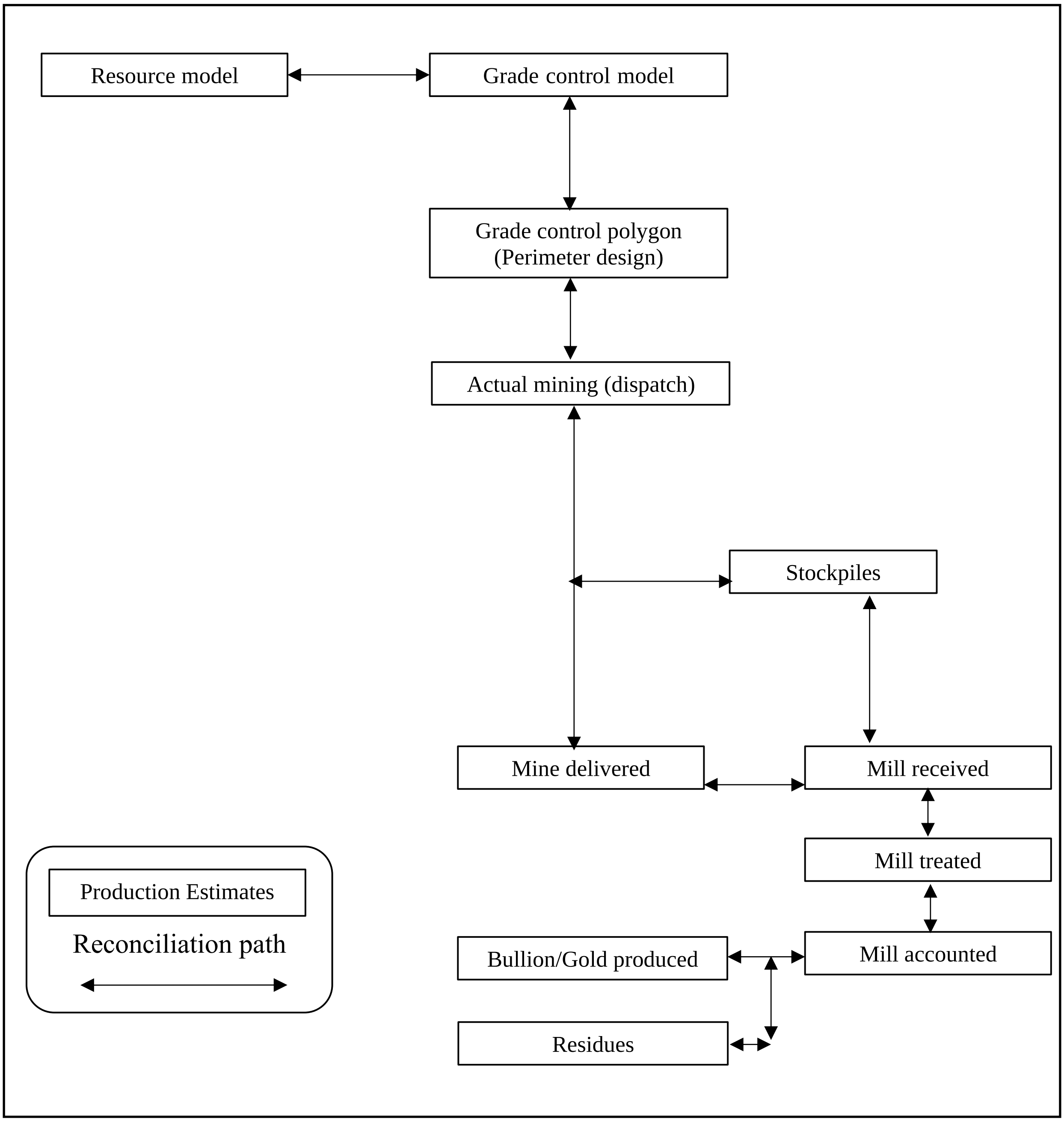

Figure 1.1 Generic model for reconciliation (Source: Researcher's concept based on Julius Kruttschnitt Mineral Research Centre (JKMRC), 2008)

Metal losses from the mining face to plant recovery have been a long-standing and a major concern for mining companies. These losses are mainly grouped into real and apparent losses. The losses which are apparent occur when metal grades are overestimated, meaning the metal was never there in the ground and therefore appears to be lost when it is under recovery. De Jager (1997) conducted a study on Freegold, with reference to Western Holdings mine, and realized that the main cause of apparent gold loss was due to the elementary methods of underground sampling and overstated relative densities. Real losses are the physical metal losses as the ore flows from the mining face to the processing plant. These physical losses can be attributed to leaving bulk ore left behind (resulting in the loss of tonnes); or a physical action that results in the loss of metal without a loss in volume (e.g. loss of metal in cracks and vents). Until time - based measurement points have been established to measure, monitor and track metal product and broken ore variables such as grade[1], volume and mass, fragmentation, density, moisture content, and location-based information, it would be difficult to determine where actual losses occur. An accurate, real-time process of tracking ore variables will improve the ore and metal accounting and reconciliation process which positively impact on the financial performance of mining companies. Poor ore and metal accounting practices lead to not knowing how much metal is in the value chain, potential physical metal losses and lower than expected mining revenues. The aim in this thesis is to develop a conceptual approach to track the flow of metal content using accurate and reliable georeferenced digital technologies and software towards achieving a digital mine, which will be discussed, in subsequent sections. Georeferenced digital technologies and software will be investigated for positioning,

[1] Grade is defined here as the quantity of the metal of interest within a mass and may be expressed in g/t or kg/t or % depending on the metal/commodity under consideration.

tracking, measuring and monitoring broken ore variables[2] to enable real-time identification of these variables passing through specific measuring points from face to the plant entry. The technologies to be investigated in this thesis includes the nickel microdot aerosol system as a viable ore tracking solution. Other existing technologies are laser scanning equipment, and communicating identification sensors (radio frequency tags). It is envisaged that this research will enable particular ore and metal types passing through specific measuring points to be linked to their sources. A conceptual 4D model of the flow of ore in an underground mine to surface will be developed in order to visualise the flow of ore relative to the mine plan.

1.2 Research background and digital technologies

The ore or metal accounting and reconciliation process in most South African mines have been a major challenge. Several efficiency factors (Shaft Call Factor (SCF), Plant Call Factor (PCF), Mine Call Factor (MCF), Tramming Factor, Extraction Factor, Overall Recovery Factor) expressed in percentages (%) have been developed and used to monitor the overall mining and metallurgical processes (Andersen, 1999). The MCF in seven AngloGold Ashanti mines in South Africa over a Seven-year period is shown in Figure 1.2[3]. Gold price over this period is displayed in Figure 1.3. The gold lost in rand value over the seven-year period is approximately 1.4 billion rand (Refer to Table 1.1 below). The total revenue obtained in this period is approximately 3.4 billion rand.

[2] Variables include volume and mass, grade for content, density and moisture content, location-based information and fragmentation. The research will monitor fragmentation after blast, whilst in the process and just before plant entry. It neither seeks to determine the types of explosive to use for blasting nor investigation of appropriate powder factor.
[3] Average MCF recorded was 70% which theoretically points to a 30% significant loss with an average gold price of US$/Oz 1450.00. MCF has steadily declined over this period.

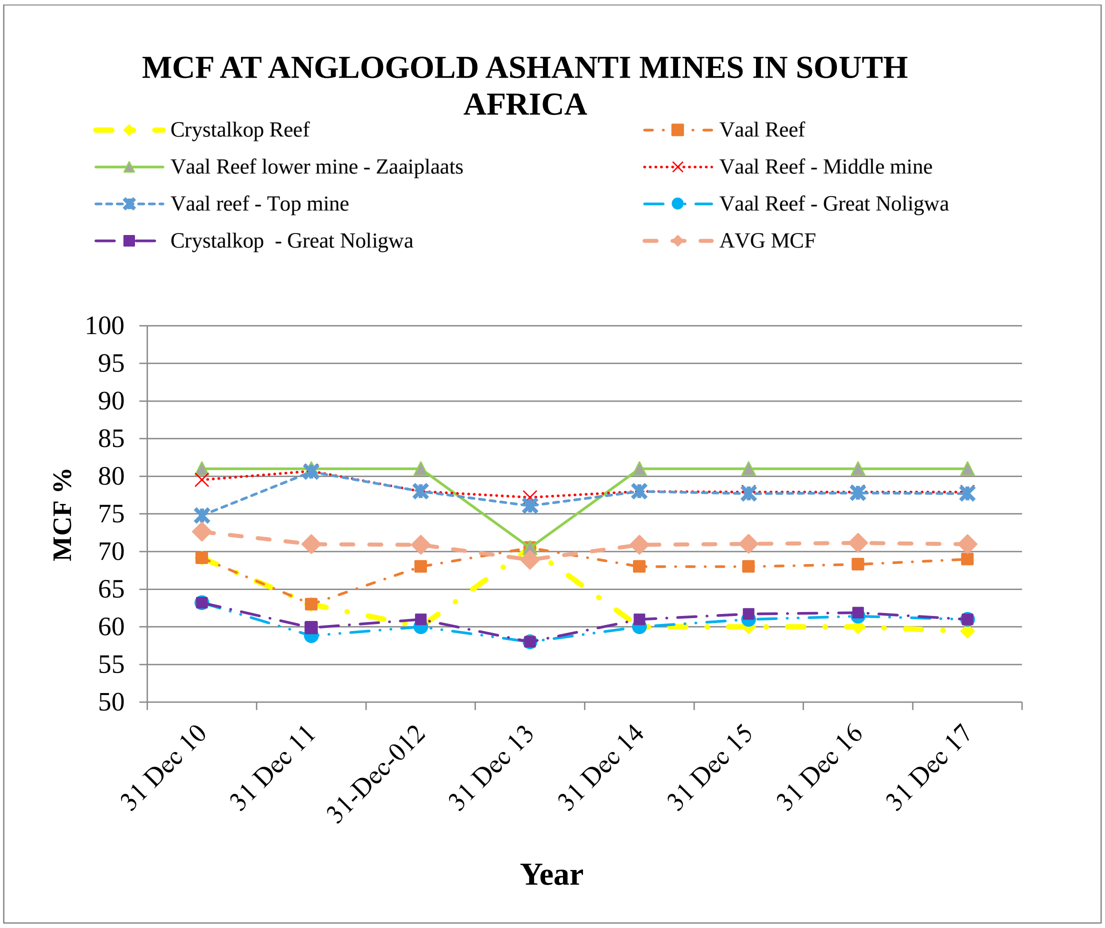

Figure 1.2 MCF at AngloGold Ashanti mines in SA (Source: MCF Data compiled from AngloGold Ashanti mineral resource and ore reserve reports 2010-2017)

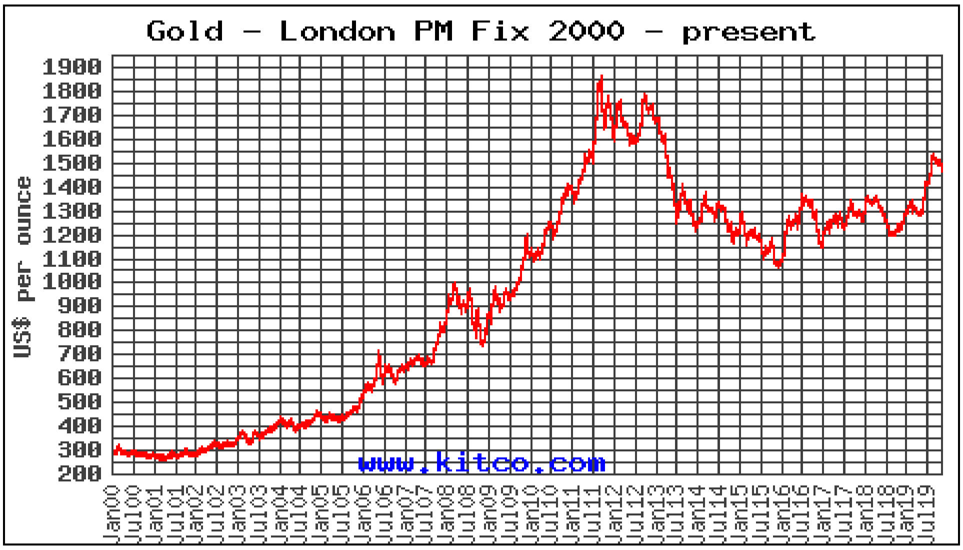

Figure 1.3 Multilayer gold price (Source: Adapted from Kitco, 2016)

Table 1.1 Monetary value of gold lost

Attributable gold production (000oz)									
	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**Total**
Kopanang	305	307	164	178	140	117	91	91	1393
Moab Khotsong	292	266	162	212	234	254	280	294	1994
									3387
								Oz	3387000
								Kg	96019,757
	Gold price								
$/oz	1227	1572	1668	1411	1266	1160	1247	1258	1351,125
$/kg	43281,2	55450,7	58837	49771,6	44656,9	40917,8	43987	44375	35,274
									47659,583
	Exchange rate								
R/$	7,3	7,26	8,2	9,6	10,83	12,77	14,68	13,3	
								Average	10,4925
		Production (kg) x $/kg x R/$ x 0.03				**1 440 492 738**			

Source: Data compiled from AngloGold Ashanti mineral resource and ore reserve reports (2010-2017)

The South African mining industry is faced with difficult choices with regard to operational uncertainties amidst global pressures. This is reflected in, for example, the total production of gold which has consistently declined in the past decade (see Fig 1.4). Deloitte Market Intelligence (2013) explored these operational uncertainties and advised that mining executives are currently faced with five basic questions pertaining to these uncertainties. These questions are around issues of profitability and safety performance, attraction and development of key critical skills, raising and distributing capital needed for South African operations and stakeholder engagements.

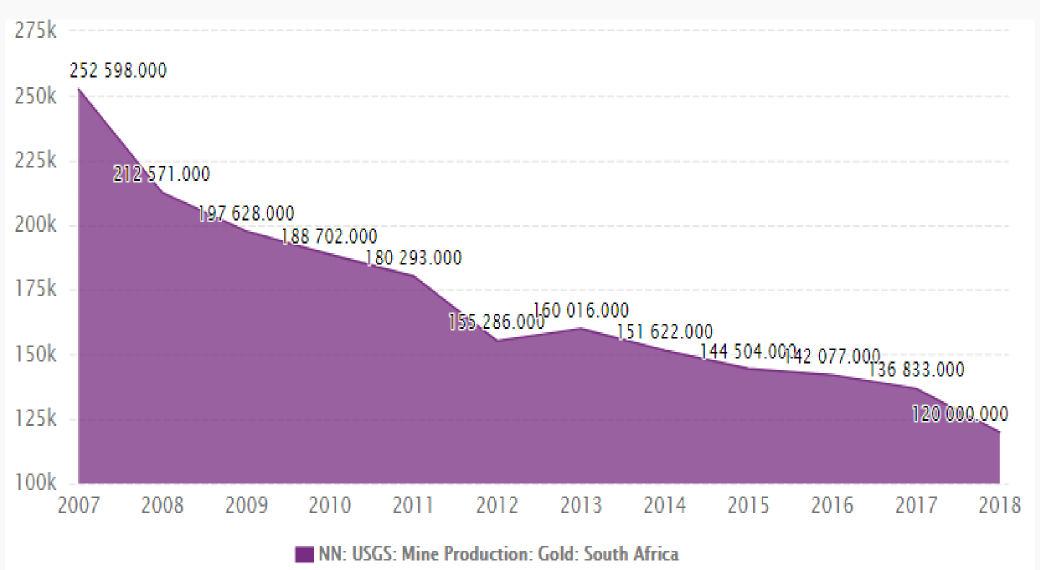

Figure 1.4 Total gold production in SA (Source: Adapted from Ceic, 2019)

Although these questions require an analytical approach to solve, Lane *et al* (2015), recommended that mining companies should encourage innovations that would solve critical skill shortages affecting the industry, focus on prospects to innovate from a technology perspective and initiate internal process changes. These strategic decisions are expected to offer mine executives a further outlook to have more control over the future of the mine which will most likely be digital (Cawood, 2015a).

South Africa, has some of the world's deepest mines and is faced with challenges including higher costs as depth increases with declining grades. This means companies have to mine at deeper levels to access reserves making extraction costs higher. Profit margins are squeezed under such circumstances and therefore require a conscious approach to prevent physical metal losses that should lead to maximizing production. This will likely result in the economic survival of mines and perhaps keep mines in production.

Systematic tracking of ore through stockpiles and bins have been a difficult task, however, the knowledge of these process hold-ups[4] is required due to their operational benefits and adherence to accounting standards. International reporting codes have been introduced to control reporting of mineral resources and reserves. An example in South Africa is section 12 of the Johannesburg Stock Exchange (JSE) listings requirements for mineral companies, exploration companies and mining companies. Section 409 of the *Sarbanes-Oxley Act* (Sarbanes-Oxley, 2002), which allows stakeholders in the mining business to demand real-time disclosure on the financial conditions of mining companies and an accurate reflection of the value of these companies. This then requires a conscious approach to the valuation of in-process inventories. According to Jansen *et al* (2009), better accounting and reconciliation can enhance the ability to forecast properly which will then lead to fewer production surprises. A further advantage is that it would result in higher mining and processing efficiencies and throughput.

[4] Process hold-ups refers to ore which occurs before mined ore is grinded and these include mine ore passes, ore bins/silos, ROM stockpiles and primary feed stockpile

1.2.1 Development of digital technologies

The use of digital technologies (computer networking, software, sensors, automation, etc.) is profound in our current world. Although there is no consensus on exactly when the digital age started; from the early 1900's after the World War One (WW1); in 1969, when the internet was first introduced; the introduction of Motorola's first mobile phone in 1973; and the presentation of International Business Machine's (IBM's) first personal computer (PC) in 1981 (Intersperience, 2015). The use of digital technologies, however, gained significant momentum after the concept of "digital earth" was first discussed by former United States vice president Al Gore in 1998 at the California Science Centre. He explained that the upsurge of technological innovations would make it possible for large amounts of data about the planet earth to be captured, stored, processed and displayed (Gore,1999). This data includes environmental and cultural occurrences. An important aspect of the information collected is that it would be "geo-referenced", meaning it will have specific locations (x, y and z) on the earth's surface.

In light of these events, several institutions and scholars have expressed their views on the concept of a digital mine (Lixin *et al*, 2000, 2003, 2004; Yaowei et al, 2009).

A digital mine is perceived as an intelligent animation which is able to provide accurate and real-time information to the mining business. Cawood (2015a) defined the digital mine as a mine that is able to observe, communicate and take action. The components of the framework of a digital mine and their functions according to (Xuedong, Lina, Xinming and Jiangtao, 2010) are in Figure 1.5 and Table 1.1 respectively.

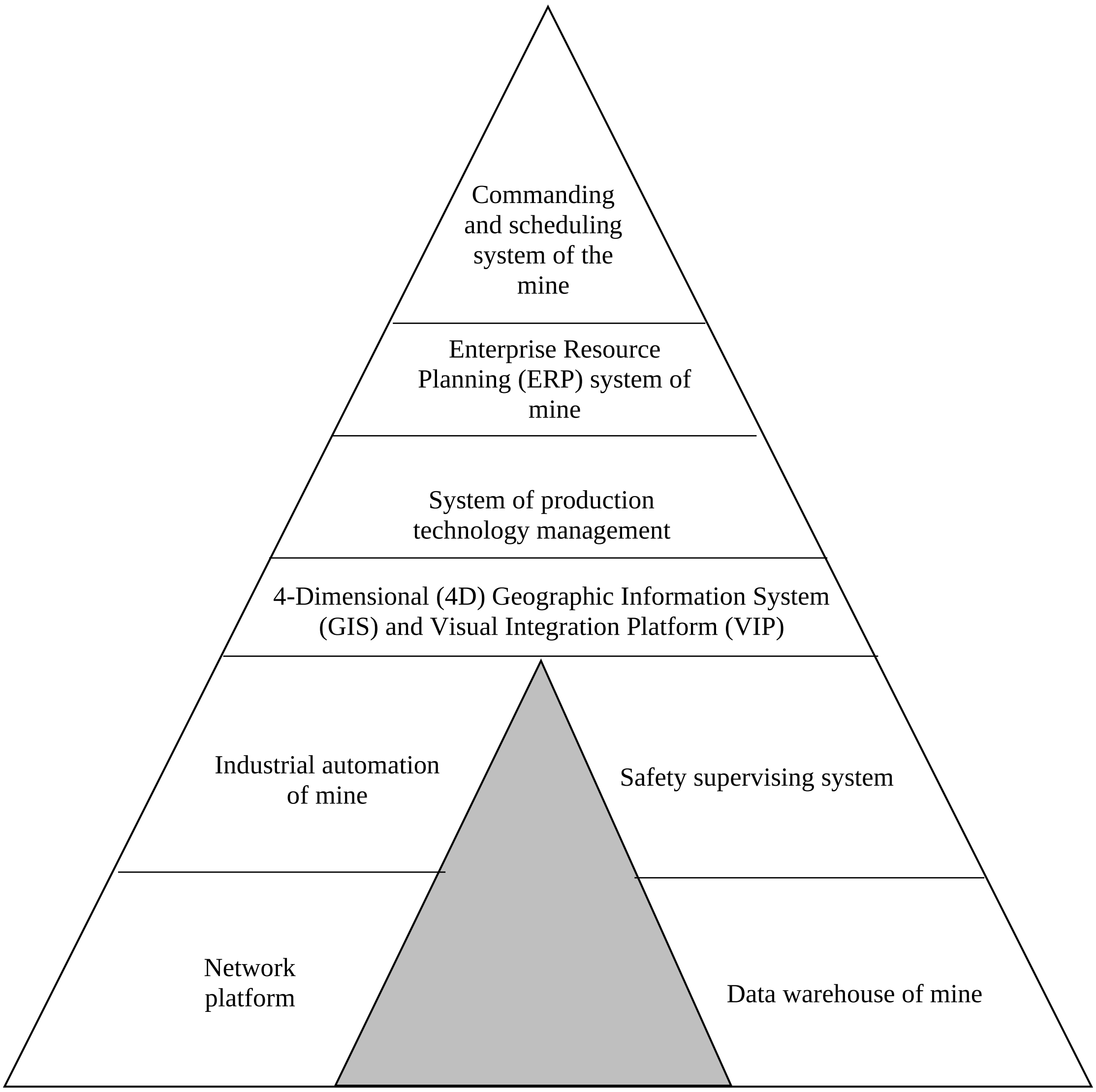

Figure 1.5 Digital mine framework (Source: Adapted from Xuedong, *et al.*, 2010)

Table 1.2 Components of a digital mine

Component	Function
Network platform	For the transmission of digital information through an intranet connection.
Data warehouse - mine	for integrating polyphyletic heterogeneous data (e.g. geological data is usually large and has complex characteristics). A data warehouse combines and generalizes data in a multidimensional space.
Industrial automation of the mine	Allows remote and automatic control through a software system by pulling resources from warehouse, safety-supervising system, a production technology management and scheduling system.
Safety supervising system	The supervising system (safety) provides real-time data from the production environment (including hydrology, surface rock movements, underground, pressure and gas emissions) to the data warehouse, the safety guarantee system

	and scheduling system to enable a decision support system.
4D GIS and VIP	Provides a four-dimensional (4D) geographic information system (based on geological coordinates and time and visual integration platform (enables a three-dimensional model of mining graphics such as ore deposits, roads, pits status, stopes, etc.).
Safety guarantee system	Enables transparent management of all objects on the surface and underground based on a 4D (GIS).
Production technology management system	This is the heart of a digital mine. It is made up of a geological survey, mine design system. Intelligent mine ventilation system, power transmission system, industrial pipeline networks, all based on a GIS.
ERP system - mine	Information management system for managers. It includes HR management system, equipment management system, material management system, transportation management system,

	financial management system, budget and cost.

Source: Adapted from (Xuedong, *et al*., 2010)

Several technologies for tracking and monitoring broken ore and metal content have been used in the past, for both underground and surface mines. Some of these technologies will be discussed in the third chapter.

1.3 Research context, assumptions, objectives, and structure of the thesis

1.3.1 Accounting, reconciliation and value tracking

AMIRA P754A code of practice was established to address challenges within the metal accounting system, which focussed on mass related measurements, sampling procedures, sample preparation and its analysis inside the metallurgical plant/concentrator only. The guiding principles employed by the code for a metal accounting system are accuracy, credibility, transparency, reliability, auditability, and practicality (ACTRAP principles).

The code presently does not address metal accounting from the mining face as its starting point. It starts from ROM, through the concentrator or metallurgical plant until the final product. This thesis will develop a conceptual approach for real-time data collection of measurement variables (grade, volume, mass, fragmentation, location-based information, density and moisture content) from in-situ to the point of delivery into the metallurgical plant towards achieving a digital mine. The site-based measurement systems for measuring these variables will provide industry guidelines towards best practice for ore and metal accounting and reconciliation.

Most mining professionals recognize the need and application for reconciliation and value tracking, however, the reality in most mining operations is that reconciliations do not really balance. Although this is not a new process, it is often branded by weighty deviations and uncertainty, which is often not understood. Effective value tracking throughout the mining process is also a challenge. Special efficiency factors such as the MCF, SCF and the PCF amongst many others, have been developed and in some cases used to adjust figures, so that planned and actual performance may correlate. Most mines are used to adjusting figures. This means there are variations and deviations that are not accounted for throughout the value chain. Considering the advancement of technological tools and the level of scientific knowledge in our current world, it is necessary to give knowledge of what happens in and around our mining environment in real/near real-time to enable proactive decisions to be made.

1.3.2 The Wits Digital Mining project

The Sibanye-Stillwater Digital Mining Laboratory (DigiMine) at Wits Mining Institute includes the development of a mock mine comprising of Nick's tunnel[5], New Concept Mining (NCM) stope[6], lamp room[7] and control room[8] in the Wits Chamber of Mines building (Cawood, 2015b). Further integration with other schools in Wits will enable the development of underground unmanned aerial vehicles (UAV), and a GIS for risk

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[5] Nicks tunnel was named after Nick Holland of Gold Fields and consists of a 70m tunnel with a crosscut breakaway which allows for one rail switch. The tunnel has a separate ventilation system for the purpose of research and a monitoring and wireless communication system.

[6] NCM stope is made up of a platinum stope panel with a complete safety and support system. It is also to be equipped with a monitoring and wireless communication system. Gold Fields and Sibanye Gold made financial contributions towards the building of the NCM tunnel

[7] The lamp room contains schaunburg designed cap lamps and rescue packs. These are designed with security and health of workers taking into consideration. The system is also equipped with monitoring and wireless communication systems. The Minetec system (mobile nodes and in-vehicle personal computer are also in the lamp room.

[8] The control room was funded by Sibanye Gold. This is where research into Campus/City GIS design; data processing and data analysis; remote visualisation; health, safety, environmental monitoring, production technology system; and hosting of a research group on preventative control measures is held.

monitoring. From a mine health and safety perspective, a real-time risk management towards zero harm of mine workers is achievable in a digital mine. This involves underground positioning of people and equipment, mapping and navigation of areas to enable frequent updates of happenings underground, action recognition and video analytics for possible detection of illegal miners, airflow modeling, dust, gas and rock movement monitoring. The blueprint for a digital mine is depicted in Figure 1.6.

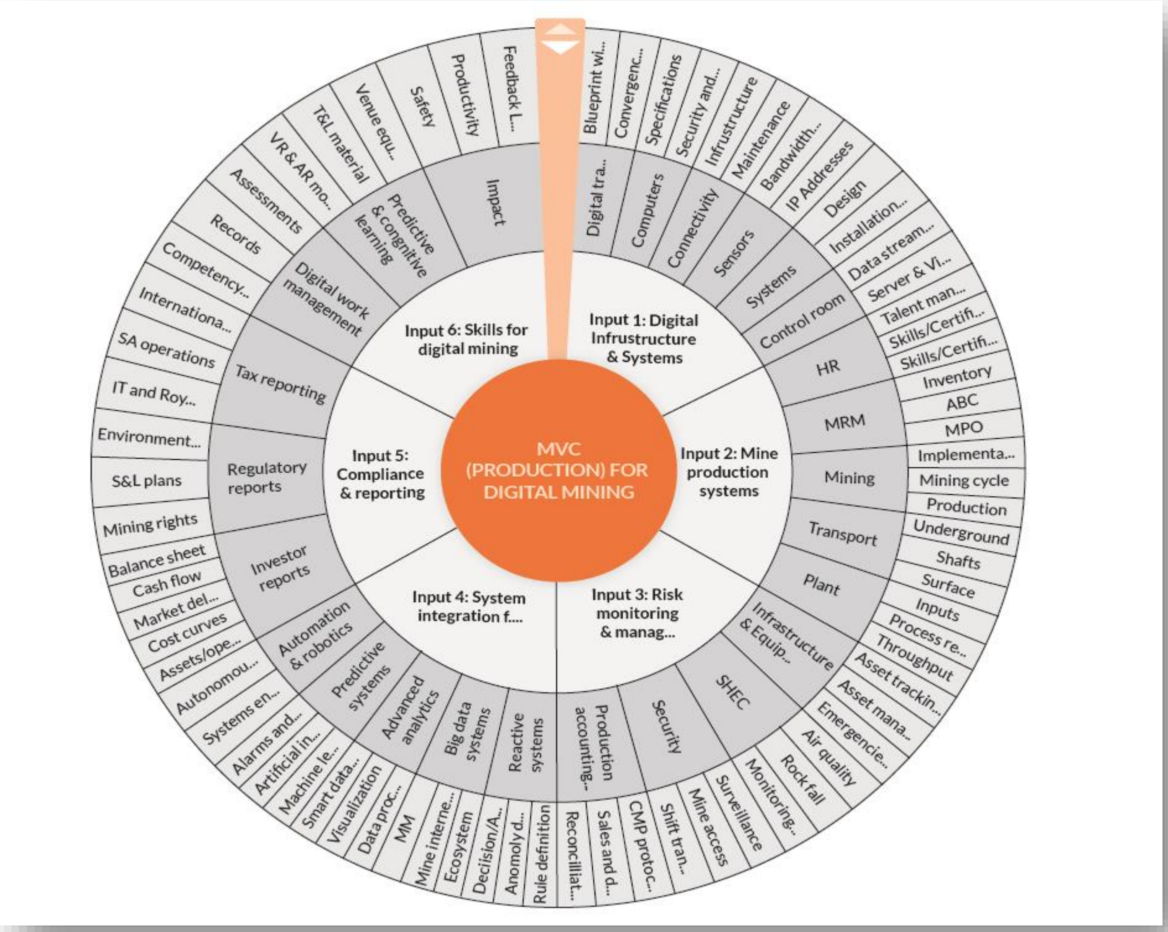

Figure 1.6 WMI Blueprint for a digital mine
(Source: Adapted from Cawood, 2019)

The time and spatial tracking of metal content from in-situ to plant entry fall under the mine planning and design category (Input 2- Mine production system of Figure 1.6). This is geared towards the identification of possible material losses especially in underground mines which is usually a complex geometrical environment.

1.3.3 Flow of ore in underground mines

The flow of broken material from underground mines to the surface and eventually through the treatment plant is naturally complex in nature. This can be attributed to the constant flow of material inside a difficult geometrical space. There are several activities along the production cycle in accordance with the mine plan (ranging from drilling and blasting, face sampling to determine grade and content, tonnage, density measurements, etc.) which the broken ore undergoes from its underground source through the shaft and then to the treatment plant and dumps. Figure 1.6 under the problem statement to be discussed in the next section, illustrates the various stages the broken ore undergoes. Broken ore and waste material from development and stoping areas are classified according to their various terminologies used in tonnage and ore treatment returns of a gold mine (Storrar, 1981). The reef and waste undergo various transportation routes, hoisted to the surface and then further undergoes physical and chemical reactions within the treatment plant until the metal/commodity is finally produced.

Current ore tracking systems underground are human dependent and there is, therefore, a higher likelihood of errors. If this problem can be overcome by introducing safe and efficient digital systems that minimise human errors, financial returns in mines will be rewarding and hence enable mines to better manage their resources in an optimal and safe manner.

1.3.4 Problem statement

The metal content that is finally produced (actual) at the processing plant/smelter is usually different from what is estimated and planned. There are several variables contributing to this variance. The establishment of physical measurement points for measuring, monitoring and tracking measurement variables are necessary, to determine where actual/physical problem areas in a mine are located. A typical problem area in underground mine (see Fig 1.7) occurs at the stage where broken ore is trammed from stoping and development areas are mixed up, tipped into ore passes and hoisted onto the surface. What happens to the broken ore and metal content within this area is usually not understood and the source of this broken ore is also usually unknown.

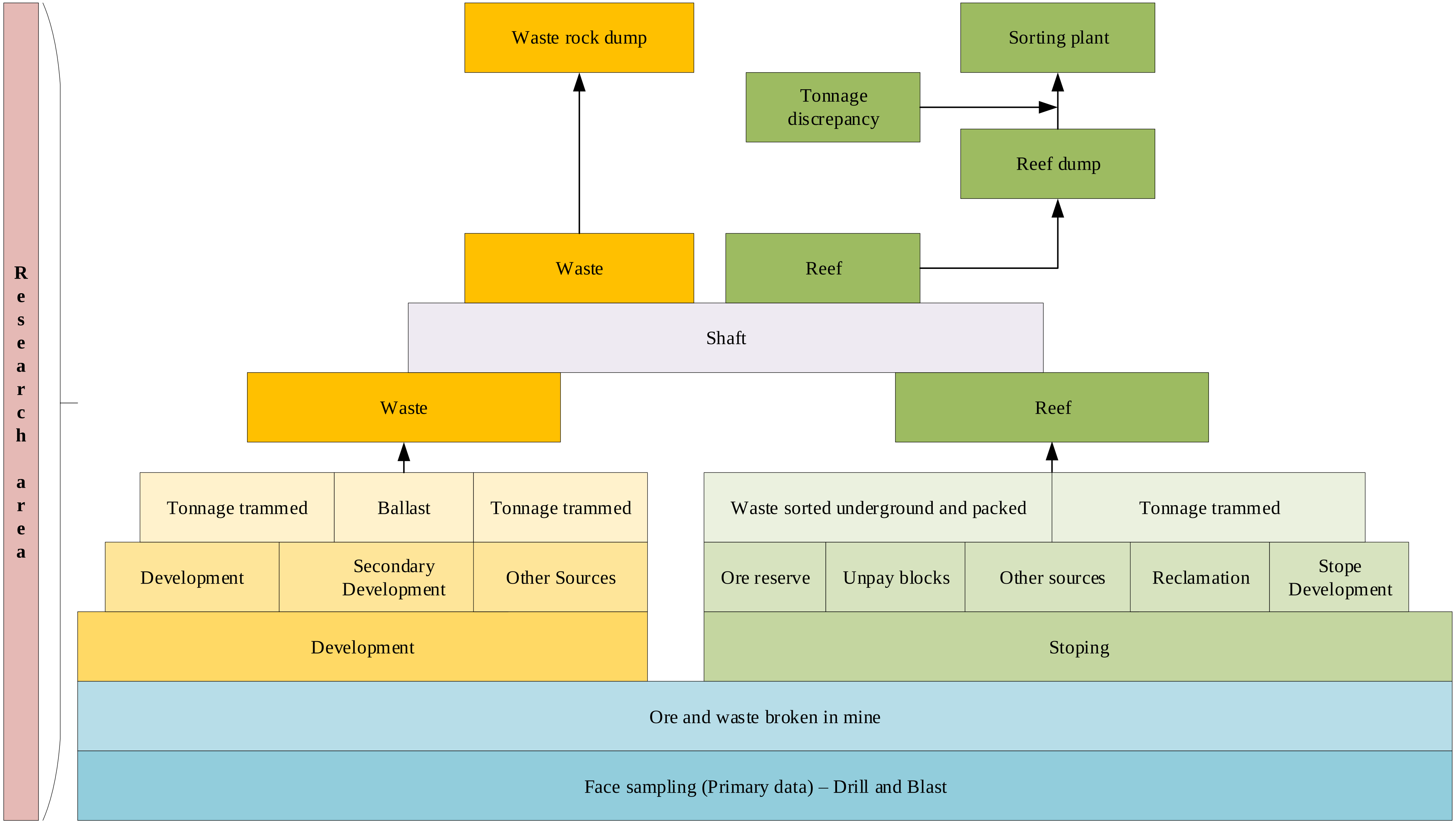

Figure 1.7 Simplified typical flow sheet of underground mine (Source: Adapted from Storrar, 1981)

1.3.5 Assumptions

These assumptions have been made to define the scope and objectives of the research:

- Tonnage measurement systems in the plant are accurate (AMIRA protocol has been adopted by the mine);
- Resource estimation method, grade control/resource models are reliable. The accuracy of block models will not be investigated;
- There are no conditional biases in the resource and grade control models;
- All engineering measurement systems have been designed, and periodic checks will be maintained and calibrated to an appropriate level of reliability (mass meters performing to their specifications); and
- Communications Infrastructure has been installed underground to enable a voice, data and video communication from underground to surface and vice versa.

1.3.6 Objectives

The objectives in this thesis are:

- To investigate new digital technologies such as Microdots to measure and track broken ore from face to mill and report their results in real/near real-time in the digital mine;
- Time and spatial analysis of broken ore from face to mill feed (Figure 1.8); and
- Develop a conceptual model for ore flow from underground to surface in a digital mine. An example is a GIS model for spatial comparison between planned and actual product quality and quantity estimates.

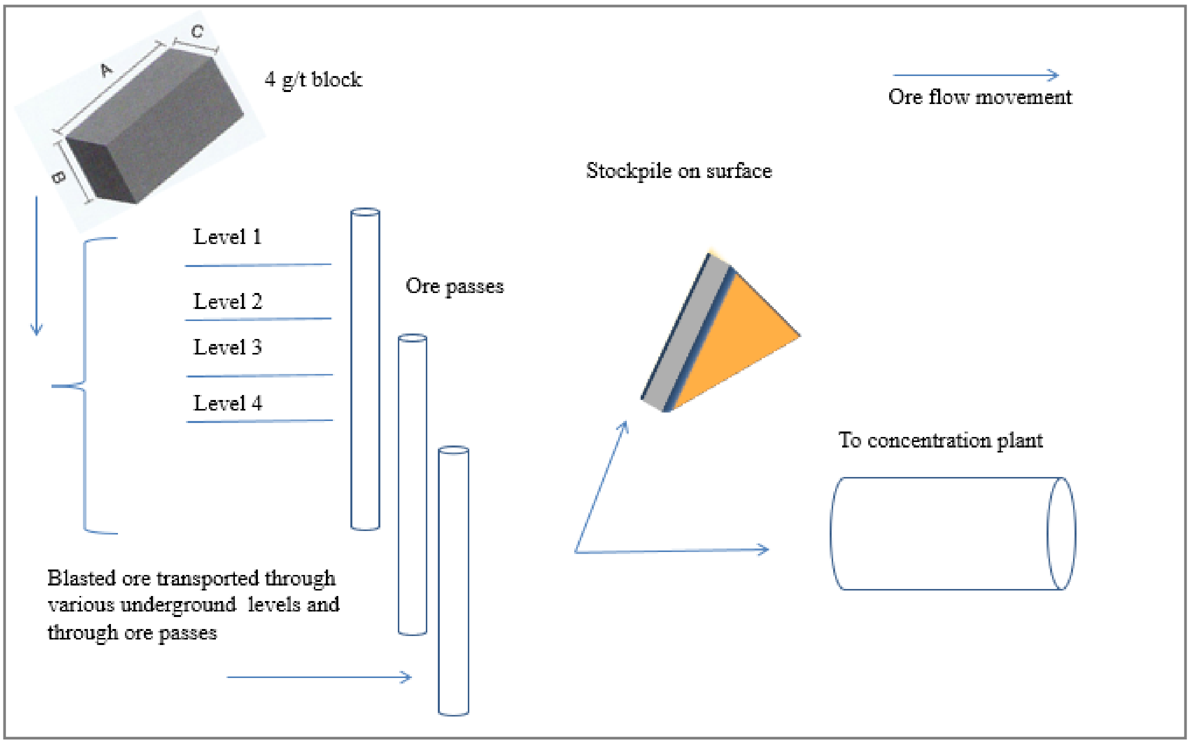

Figure 1.8 Time and spatial tracking of blasted ore from face to mill fee

(Source: Researcher's concept, 2016)

1.3.7 The expected outcome of research and benefit to the industry

This thesis will cover a conceptual model of real-time data collection and reporting in real/near real-time using combined digital technologies and systems. The conceptual model is envisioned to enable particular ore types passing through specific measuring points to be linked to their source so that problem areas in a mine can be identified instead of assuming there is a general problem on the mine. Immediate actions can then be focused on these problem areas.

Figure 1.8 depicts the architecture for tracking metal content and broken ore variables in an underground mine. It can be perceived as a systematic approach to tracing physical metal content in a mine, whilst making it possible to identify potential and specific problem areas for focused and immediate actions to be taken. A three-dimensional (3D) ore flow model in relation to the mine plan can then be developed.

The workflow for ore flow modeling is shown in Figure 1.9.

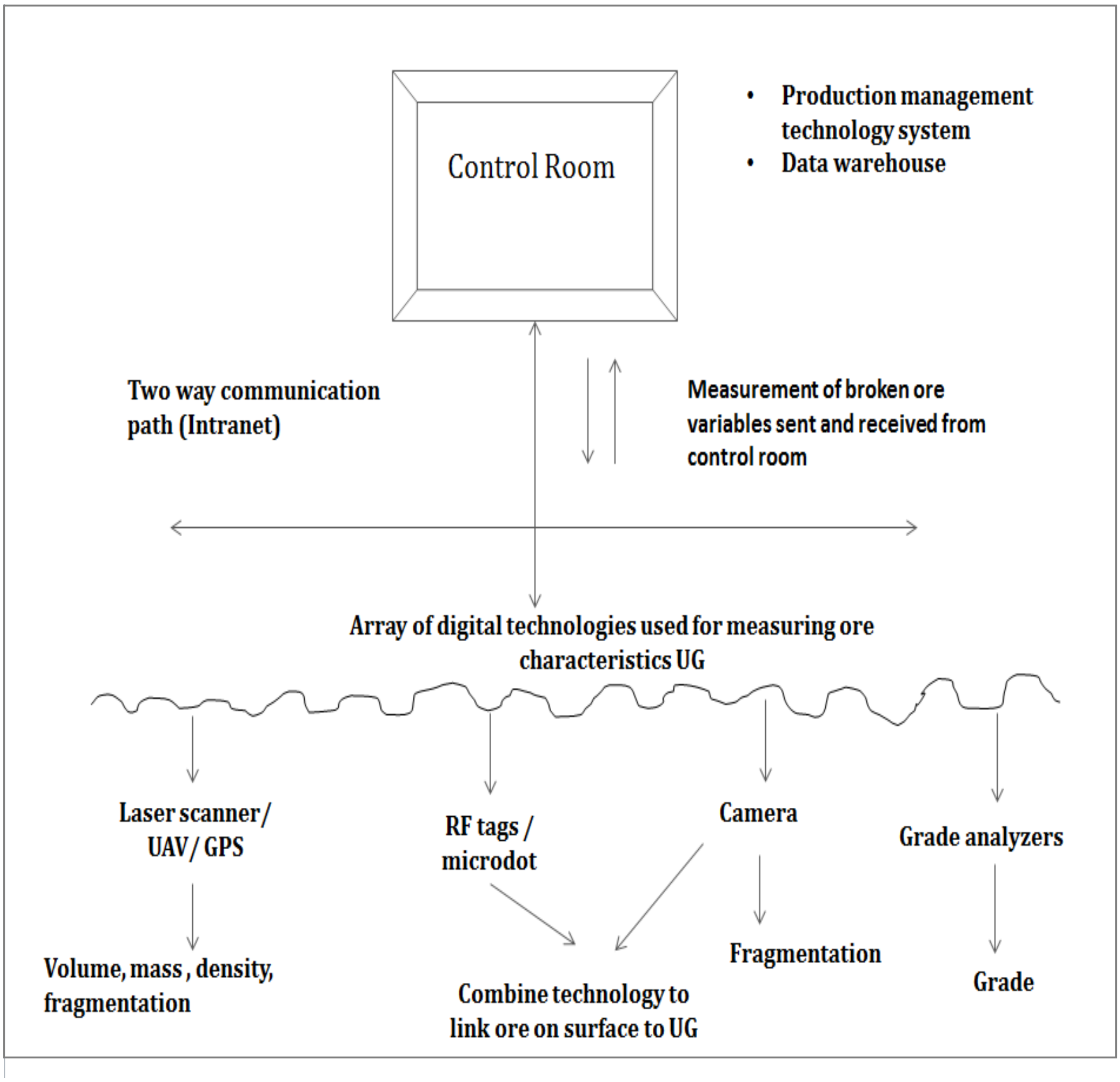

Figure 1.9 Conceptual architecture for tracking metal content and its variables in an underground mine in real-time (Source: Researcher's concept, 2015)

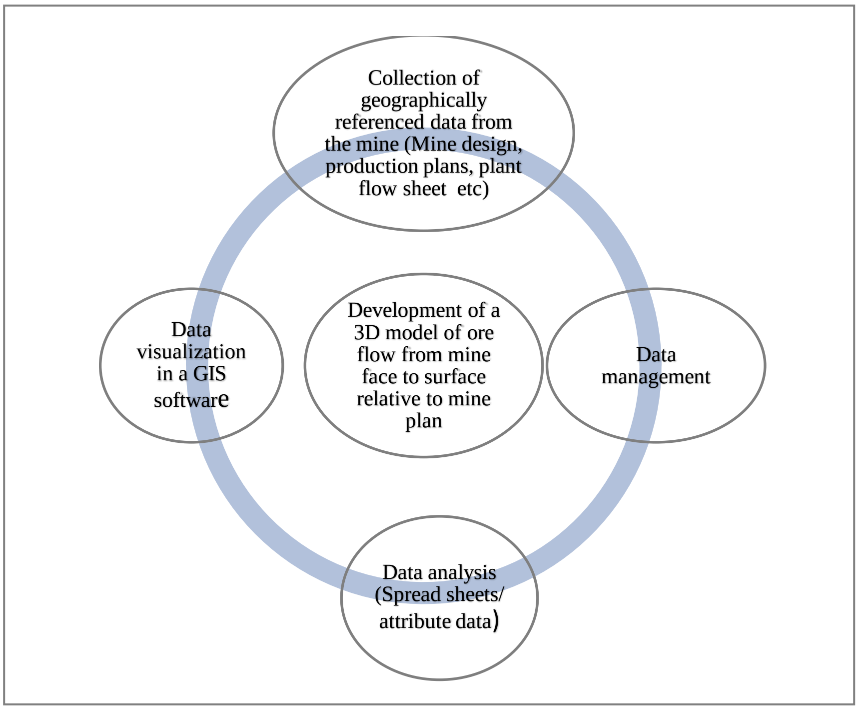

Figure 1.9 Workflow for ore flow modelling (Source: Researcher's concept)

1.3.8 Research question

From the previous sections, it can be noted that the thesis seeks to provide an answer to the question, "Are combined digital technologies suitable for tracking, measuring and monitoring metal content from the mining face to plant entry?

1.3.9 Thesis structure

The thesis is made up of 10 chapters followed by a list of references and Annexes.

Chapter 2 is dedicated to a literature review on MCF issues and investigations conducted in the past.

Chapter 3 is a review of technologies that have been tested in the past for value tracking.

The 4th chapter discusses leading mine planning and reconciliation software options towards technologies that are possible.

Testing of technologies such as the Microdots aerosol system will be discussed in chapter 5. The 6th chapter is dedicated to a theoretical approach to volume and In-process inventory measurements. Chapter 7 is a case study for real-time material tracking using a typical underground mine as an example. The 8th chapter develops a conceptual time and spatial tracking of metal content from in-situ to plant entry. An implementation process for metal tracking from underground to plant entry is also developed. The 9th chapter is an assessment of the combined digital mining technologies discussed. The 10th chapter finalises the thesis with conclusions as well as recommendations.

1.4 Conclusion

MCF in some South African AngloGold Ashanti mines is about 70% over a seven-year period, which theoretically means a 30% loss of metal. The loss in monetary value over this seven-year period has been approximated at 1.4 billion rand. The total revenue obtained in this period is also about 3.4 billion rand. The problem of metal losses from the mining face to recovery is a major concern to mining companies. An example is when actual measurements and planned quality, quantity and time estimates from various measurement systems do not reconcile. Although there are apparent and real losses that occur in this process, the research is focused on identifying possible real metal losses. Digital technologies are investigated in this thesis for tracking, measuring and monitoring metal content and broken ore variables (metal content, volume and fragmentation, density and moisture content, location-based information) from the face to plant entry. These technologies include nickel microdot for tracking parcels. A conceptual model of the flow of material from the mining face (underground) to the surface relative to the mine plan will be developed.

The second chapter is a discourse on the theory of MCF and related issues. MCF investigation and proposed solutions which have been conducted in the past on various mines will be discussed.

2 Mine Call Factor theory towards an implementation model for digital mine

2.1 Introduction

The MCF theory is generally acknowledged but investigating discrepancies are not fully clear. Its definition means that if the process of sampling, assaying, and the measurement of tonnage in a mine and plant are flawless and without material losses at any stage during handling and processing, then MCF of 100% should be expected. Factors influencing the MCF include the sampling and assaying strategy of the mine, tonnage measurements, mass and density measurements at every stage of mineral development, transportation of materials to the plant and the ore and metal accounting and reconciliation plan. Although apparent gains or losses are not an integral aspect of the thesis, the chapter discusses the significance of MCF with reference to sampling practices in the South African mining industry. The issue of ore loss and dilution is also discussed. Tonnage measurement procedures are also covered in this chapter. An implementation model for tracking broken ore variables in the context of digital mining is also discussed. The chapter concludes with further justification for the need to track ore parcels using various georeferenced technologies with the aim of modeling ore flow in the mine.

2.2 Mine Call Factor theory and calculations

Storrar (1981) defined MCF as a fraction (expressed as a percentage) of the specific product accounted for in recovery plus residue, to the corresponding product called for by the mine's measuring method. The is mathematical expression is:

$$\text{MCF} = \frac{metal\ produced\ in\ recovery\ plus\ residue}{metal\ called\ for\ by\ mines\ evaluation\ method} * 100\%$$

This means that if sampling, assaying and measurement of tonnage in a mine and plant are without flaws and there is no material losses in handling and processing, then the MCF should theoretically be 100%. A tonnage discrepancy known as a shortfall occurs when the surveyor's calculated tonnage is lesser amount than the plant tonnage. This suggests losses somewhere along the ore flow from (underground or surface) to the plant for recovery. Tonnage discrepancies is an excess when the surveyor’s intended tonnage is more than the plant accounted tonnage.

Metal content losses are classified as either real or apparent. In an evaluation process, when metal contents are overestimated, this would result in a metal called for that is apparently not present, and contribute to apparent losses. This further implies that there can be apparent gains, in this case, an underestimation of metal content and a low metal called for will result in an apparent metal gain. The apparent gains are however rare in occurrence as most mines report MCF of less than 100% for most of the time.

Other factors that contribute to apparent gains/losses include unsuitable sampling standards, incorrect application of standards and wrong relative density applied. This occurs in the geological modelling process, the evaluation of block models. Apparent gold loss was noticed and explained by De Jager (1997) when he realised that the correlation between the MCF and the stope grade at Western Holdings mine was statistically insignificant, and therefore the grade estimations accuracy was questionable. The reason for apparent gold loss was attributed to traditional sampling methods of ore reserves and wrong relative density applied.

Real losses are actual metal losses. Examples are gold locked in crevices during tramming and in the plant, and also during hoisting, extraction, and processing. These essential issues tend to keep the MCF below 100% on average. Cawood (2003) explored the underground face sampling on narrow reefs and realised that the MCF is not a reliable for investigating metal losses. This is because it spans over a wide range of technical disciplines, ranging from orebody modeling for ore reserve management plus activities at the mining face until the metal is produced in the smelter/plant.

Storrar (1981) suggested that a persistently low MCF (below 80%), should be investigated by the management of the mine because the sampling process may be over-estimating the treated content. The challenge however here is when the sampling processes, assaying and extraction procedures are all compliant to the company's standards, it then becomes difficult to determine where actual problem areas are. Personnel are however encouraged to avoid manipulating ore accounting figures to reach an MCF that is perceived as acceptable.

2.3 Metal accounting theory

Metal accounting is an important part of mineral resource management. Its objective is to reconcile the physical metal content with estimated content (Hills, 2000). The movement of materials carrying metal in an underground mine is typically complex. These complexities arise from issues such as Hills (2000):

- Unalike and several mining faces;
- Several shafts/pits with allocations of interplant materials sometimes regional refinery getting material metal bearing from unrelated mines;
- Production loss due to dilution of material and mistakes such as transfer or waste to plant and ore to waste; and
- Multiple storage points including bins and stockpiles.

The complexity of material flow in especially underground mines requires a safe and systematic approach in determining the metal content (which is a product of the tonnage and sampled grade) between any two points within the flow. Ore accounting is defined as a systematic approach for the recording and representation of ore valuation, mine grade and ore treatment statistics of a mine (Janisch, 1973). The objective is to present statistical data in a format that makes it easy to track and monitor the flow of materials from the source to the plant for treatment. This would enable management to scrutinize performance and analyse potential profitability. Statistical data is used by management to generate reconciliation factors and efficiency factors such as the MCF for planning purposes. Records of statistical data also assist management in measuring planned performance against actual one. The translation of physical losses into monetary values highlights areas with losses which are monetary (Storrar, 1981). This would enable management to focus on specific areas and propose specific measures to implement for further improvements.

2.4 Ore flow balance sheet

The flow balance sheet indicates all the sources of ore. In underground gold mining, these include the ore reserve, not in reserve (NIR), development sections and other sources. Reasons for ore losses along the flow must be captured in the standard ore flow sheet. Table 2.1 is typical ore accounting sheet which shows the various sources of ore and their respective metric tons, value (g/t) and content (g). The ore flow sheet in Annex A1 similarly shows an ore balance sheet where categories of ore are either added or subtracted at each stage.

Table 2.1 Ore flow balance sheet

SURVEY				PLANT			
Source	**Metric**	**Value(g/t)**	**Content (g)**		**Metric tons**	**Value(g/t)**	**Content**
Mined From:				Mill recovered	TZ	VZ	CZ=TZVZ
Ore Reserve	T1	V1	C1=T1V1	Mill discard (residue)	TR	VR	CR=TRVR
NIR	T2	V2	C2=T2V2	To mill	TM=TR+TZ	VM=CM/TM	CM=CR+CZ
Development	T3	V3	C3=T3V3				
Other Sources	T4	V4	C4=T4V4	From unmilled stockpile	TA	VA	CA=TAVA
Hoisted	TL=T1+T2+T3+T4	VL=CL/TL	CL=C1+C2+C3+C4	From HMS. plant	TH= TM-TA	VH=CH/TH	CM-CA
To stockpile	T5	V5	C5=T5V5	HMS. Discard To HMS. Plant	TH+ TB	VB	CB=TBVB
Shortfall	S=TP-TL=T5	ZERO	ZERO	Hand-sorted waste	TW	VW	CW=TWVW
To plant	TP	VP=CP/TP	CP=CL-C5	To plant	TP=TH+TB+TW	V=C/TP	C=CH+CB+CW
Mine Call Factor = 100CM/CP							

Source: Adapted from (Janisch, 1973:237)

The application of the ore flow balance sheet in an underground mine is verified with the extract in Annex A2 from a month’s production records of a mine. The calculations determined include the survey discrepancy (shortfall/excess), MCF and Plant Recovery Factor. The results are displayed in Annex A3. Apart from identifying content discrepancies, it is also important to consider tonnage discrepancies. The discrepancy known as a shortfall occurs when the total trammed to the surface is less than what was hoisted as the reef.

The reasons for a shortfall based on a group of mines according to Storrar (1981) are:

- Inadequate measurement of stope widths and areas;
- Using inaccurate rock densities for tonnage calculations;
- Scaling of walls of excavations of headings and incorrect allowances for sag;
- Tearing up foot walls with scrapers;
- Mistakes in the measurement of cross-sectional areas of headings;
- Incorrect track ballast allowance; and
- Inaccurate waste estimate that is packed under sorting surfaces in spillage drains.

Other possible causes of shortfalls include:

- Underestimated dilution;
- Missing losses at production areas, short-term stockpiles, and spillages;
- Wrong transport tonnage factor; and
- Wrong use of densities (in-situ and soil).

As explained previously, a discrepancy is an excess when the surveyor's tonnage that is calculated is larger than the tonnage accounted for by the plant. However, tonnage discrepancies are often shortfalls due to large parts of waste that is trammed as ore. Necessary steps should be taken to minimize such errors.

2.5 Components of Mine Call Factor

The issues of MCF vary from mine to mine because of the nonconforming nature of mining activities. There is a need to establish a systematic and scientific approach to differentiate between realities and misconceptions. According to Cawood (2003), it is crucial to identify and analyse the various components of the MCF for a successful investigation. The components according to Storrar (1981) includes the following nine variables with focus on underground gold mines at that time:

1. Surveyor's measurements and calculations;
2. Current sampling of ore sent to mill;
3. Rock packed underground as waste;
4. Rock sorted as waste on the surface;
5. Ore picked on the surface from waste;
6. Tipping of ore, and car factors under certain circumstances;
7. Underground accumulations of ore and sweepings;
8. Losses from theft of gold in the plant; and
9. Assay bias and allowance for silver content in gold assaying.

Although there are numerous criteria influencing a poor MCF, Andersen (1999) observed that these, when investigated individually, do not necessarily show an improvement in the MCF. This was also anticipated by Springett (1993), who indicated that the purpose of MCF shouldn't be limited to reconciliation purpose. Springett (1993) advised that the information derived should be used to solve problems. This is an important observation in the context of digital mining which has the potential to collect and analyse big data in mining.

Tetteh and Cawood (2014) outlined the MCF components from a surface mine perspective, focusing on mining activities before grinding and milling with AngloGold Ashanti Iduapriem Mine as a study case (Figure 2.1). These activities cover both apparent losses (resource/reserve estimation and survey tonnage calculations) and physical losses which may occur during sampling, blasting, and material movements and clean up exercises.

Figure 2.1. Variable components of the MCF for surface mines (Source: Tetteh and Cawood, 2014)

2.6 Mine planning and reconciliation of bulk commodities: case study

Whereas content tracking and reconciliation are critical for metal producing mines, tonnage reconciliation is the critical issue for bulk commodity mines for e.g. coal. The process of coal reporting through reconciliation between planned and actual coal produced involves an integrated mine planning process and reporting codes such as the South African Code for Reporting of Exploration Results, Mineral Resources and Mineral Reserves (SAMREC CODE). Measurements are important for tracking and reconciling coal recoveries. These allow for consistency during measurement, reconciling and coal production reporting. For this to be fruitful, Mining, Plant personnel, Contractor and Technical must review their systems of measurement for tracking and monitoring production from pit to customer. The planning and operating practices must be aimed at improving recovery of coal, meet operational targets and governance requirements. Performance across the coal production chain requires substantial investment in terms of measuring tools, engineering, supervision and reporting. The next subsections outline some of the critical considerations in terms of design for accurate coal measurement and reconciliation for integrated mine planning.

2.6.1 The integrated mine planning process

Integrated mine planning is an initiative that imitates an optimized interaction between people, processes, and systems for safe, sustainable, and profitable production (Cawood and Richards, 2008). Although the process varies from mine to mine, it should follow a simple structure like the one in Figure 2.2. Cawood and Richards (2007) pointed out some opportunities for coal mine surveyors to add value at the operational and corporate heights of the mining company. These prospects include playing a role in mineral accounting and quality assurance to meet requirements of the mine, specifications of the market, as well as reporting. This should be done in a way that is consistent with business drivers along the mine value chain.

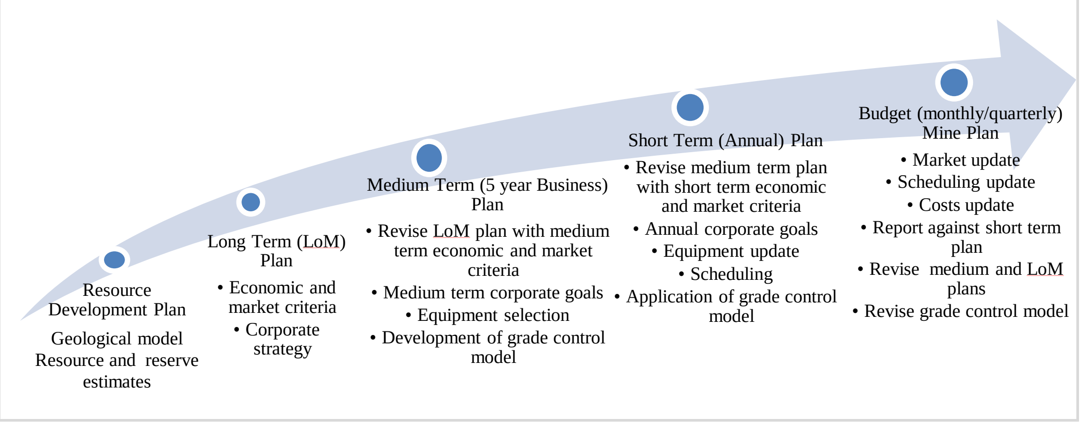

Figure 2.2 Integrated mine planning process

Source: Cawood (2015)

The mine planning process starts with the reporting of Resources and Reserves based on the SAMREC Code. The Reserves form the basis of the resource development plan (RDP), which gives the first benchmark for the reconciliation of coal. RDP is basically used to identify economic and market criteria. Inputs such as the mine's corporate strategy also inform the long-term plan. A medium-term plan which is usually a 5-year business plan is developed from the constant revision of the life-of-mine (LoM) plan, taking into consideration medium-term economic and market criteria, corporate goals, equipment selection, as well as the grade control model (GCM). The short-term plan which is usually the annual plan is a refinement of the medium-term plan, and other inputs such as short-term economic and market criteria, annual corporate goals, updates of equipment, scheduling, and the refinement of the GCM. The final stage of the planning process is the budget mine plan which is done monthly or quarterly. The scheduled blocks (defined by SAMREC as the smallest modeled volume in the Reserves database and lowest scheduling entity in the planning hierarchy) are created with coal quantities and qualities calculated for each block. Adjustment factors are then applied to estimate coal resources, ROM coal reserves, and marketable reserves. Morley and Moller (2005) characterised some observations in the planning process into four main themes:

- Resource/Reserve estimation and mine planning (includes long, medium, and short-term planning plus annual reporting and budgeting);
- Mining, which includes resource/reserve block depletion (dispatch, survey data, and stockpiling information);
- Plant processing (feed and product); and
- General observations and best practices.

The themes of a planning process outlined by Morley and Moller (2005) and the definition of an integrated mining process by Cawood and Richards (2008) both stress the need for best practices in measurements.

All the happenings at every stage of the planning process are replicated in the GCM, which is the best available estimate of the coal to be mined (defined by SAMREC as the coal in-situ within a scheduling block and within a working section targeted for mining and expressed as in-situ tons at in-situ moisture) and the products it will yield. This makes the GCM fundamental for the comparison of planned and actual mining recovery. Opportunities become available to advance the definition of the coal to be mined as operations approach the area of interest. These areas of interest as well as their descriptions are shown in Table 2.2.

Table 2.2. Considerations for improving coal definition during operations

Area of interest	Description
Highwall mapping	Highwall from previous strip to be mapped to characterise the overburden to be blasted in the previous strip. Define the floor and roof horizons for the low wall of the next strip
Strip survey	Strip surveys for grade control include coal floor profiling, losses underneath, roadways and potential loss due to accumulations against the high wall.
Top of Coal drilling and or strip sampling	Core drilling might be required from an exposed coal roof to upgrade the definition of coal quantity and washability.
Mining practices	Mining equipment and method have an impact on the scale of dilution and loss.

Preparation plant simulation	Available representative washability data from coal drilling or pit sampling would improve the short term estimation of preparation plant yield.

Source: Tetteh and Cawood (2017)

The coal Resources are a subsection of the total tonnage of coal in-situ (defined by SAMREC as coal in the ground, before exposure and at in-situ moisture and density). According to SAMREC, the coal Reserve is the economically mineable subset of the coal Resource. A mine plan that is economic as well as adjustment factors are required to generate coal Reserves (ROM tonnages) and marketable Reserves from the coal Resource. These factors must describe what is expected in mining and preparation of plant recovery for coals from the different parts of the Resource. The connections between coal Resources and coal Reserves is depicted in Figure 2.3

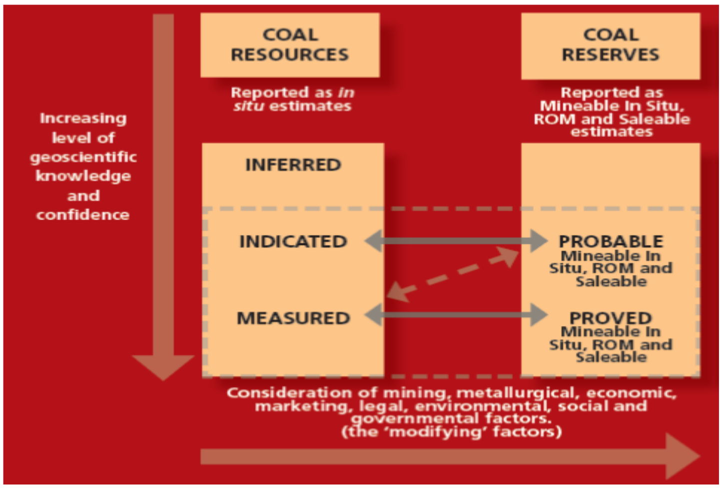

Figure 2.3 Relationship between coal resources and coal reserves (Source: SAMREC, 2016)

2.6.2 Coal transition from in-situ through ROM coal reserves to a saleable product

In calculating the quality and quantity of the ROM coal reserves, the following should be considered:

- Mass (tonnage) after allowing for mine planning factors, moisture content, geological losses, mining dilution, mining losses; and
- The coal quality must be expressed in parameters that are relevant to specific applications for e.g. Eskom coal, Export coal, etc. and ash, volatile matter, sulphur, coking properties, calorific value, etc.

Saleable coal is the quality and tonnage that is available for sale, either in the raw ROM state at specified moisture content or after beneficiated ROM coal Reserves have produced materials at specific qualities, moisture contents and ranges in terms of sizes. For raw ROM products, the industry norm for product yield is typically 100%. Discard and Reject coal from the processing plant or mining operations should be measured for effective coal flow comparisons and reconciliations. Figure 2.4 shows the basic relationships when transitioning from in-situ to the saleable product.

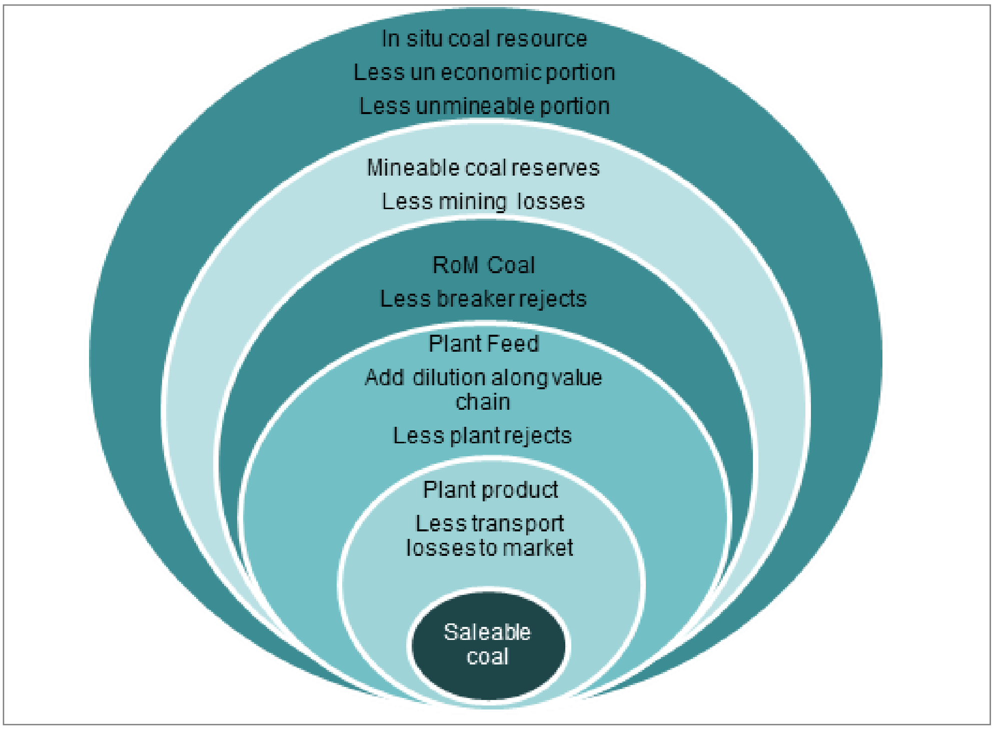

Figure 2.4 Transition of coal from in-situ to saleable product (Source: Cawood 2015a)

The outer and larger circle represent the In-Situ Coal Resource. Some of this may be uneconomic or unmineable and is therefore excluded from the coal identified for mining. Adjustments are applied to the quantities and qualities of the coal represented by scheduling mining blocks as part of the planning process. Such mining blocks are informed mainly by the mining method that is applied. The mining process will inevitably fail to recover all of the targeted coal in a block and will include some dilution from adjacent materials. This mixture then becomes the ROM coal that is removed from the pit. ROM coal may be placed in an intermediate stockpile and later reclaimed before being fed to the plant or power station either alone or in a blend consisting of coal from another mining area or areas.

The first beneficiation process usually involves crushing the coal in a rotary breaker which also separates large hard fragments as reject. The remaining material is then stockpiled as crushed coal and is subsequently reclaimed as the feed to the preparation plant. The breaker rejects and the yield expected from the preparation plant must be estimated for each scheduling block, based upon the relevant properties of the coal and dilution materials. Simple adjustment factors based on available borehole core samples tend to be used, in conjunction with broad efficiency factors, to generate estimates of the marketable reserves. Adjustment factors are often used in the industry to obtain a reasonable estimate of Saleable Reserves (represented by the smallest circular shape in Figure 2.4, called the yield). However, the general nature of these adjustment factors makes it difficult to back-analyse the performance of discrete processes or to guide specific improvements of field performance. The condition of coal is altered as it undergoes mining, handling, treatment, and transport processes. Other processes such as breakage, losses, contamination, and exposure to the ingress of moisture are all possible means of altering the characteristics of the coal. These effects need to be evaluated for every coal type and at all stages of the coal flow

2.6.3 Reconciliation between planned and actual in the coal industry

The basic planning and reconciliation process is illustrated in Figure 2.5. Estimations are based on large data and assumptions to create block models. Based on these models, mining engineers are able to forecast in terms of grades, tonnes, and expected income. Finally, the actual is what has been recovered after a production period. Planning and scheduling are based on data and assumptions, reconciliation is based on what is actually produced.

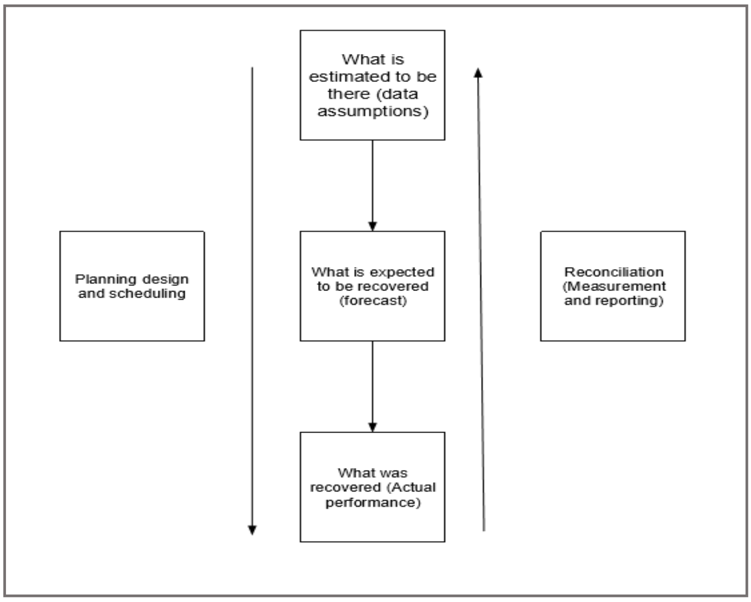

Figure 2.5 Basic reconciliation process (Source: JKMRC, 2008:520)

The reconciliation compares what was recovered with what was expected to be achieved so that the planning and production processes can be continually refined and improved. This appears to be basic but the entire reconciliation process can be a complicated one. Complications can come from the inadequate definition of reserves, inadequate monitoring of production performance, difficulties tracking coal through stockpiles and blends and inconsistencies between the times when measurements are taken and when results can be applied (JKMRC, 2008:520). Highly sophisticated tools are developed and used for modeling, planning, measurements and reporting by the industry to tackle some of these challenges.

2.6.4 Critical measurement points and reconciliation

For a typical coal surface mine and depending on the market requirements and mining areas serving a processing plant, one can expect the following measurement points:

- Measuring Point 1: Output of the Mine Planning and Scheduling Process;
- Measurement Point 2: Post-Mining Pit Survey and Highwall Mapping;

- Measurement Point 3: Feed ROM tonnes delivered to the plant;
- Measurement Point 4: Coal product; and
- Measurement Point 5: Coal sales tonnage.

Table 2.3 summarizes the measurement points, measurement variables at each critical measurement point, data processing, reconciliation and reporting procedures carried out at each measurement point for the purpose of developing protocols at each critical measurement point throughout the coal production chain.

Table 2.3 Measurement points along a coal product

Measurement point	Measurement Variables	Processing	Reconciliation	Reporting
MP1- Output of mine planning and scheduling process	Tonnage, quality, and locality of planned coal. Mine plan and grade control model – Area, volume/mass, relative density, losses and dilution, quality parameters such as Calorific Value (CV), ash content, and moisture content.	The volume of coal in-situ obtained by multiplying the modeled block plan area by the vertical thickness. The volume of coal in the ground is the same as the volume of coal at in-situ moisture. Estimation of loss and dilution measurements of coal mass accompanied by moisture content and then the mass of coal minus moisture to be determined. Coal density is obtained from the exploration of borehole core samples. In-situ mass of coal is calculated from the in-situ volume of coal and relative density of coal at in-situ moisture. Appropriate adjustment of ROM coal is first to estimate the mass of in-situ coal and then consider any moisture adjustments gained or lost from the in-situ to ROM.	Comparison of grade control model to coal reserves.	Production planning information generated by the mine planning department. Report generated at the start of each month and contains information per seam and mining block.

MP2- Post- Mining Pit survey and Highwall mapping	Volume/Mass of coal and waste material. Surveying and mapping of the final floor, high wall, and low wall edges after mining. Swell factors to ensure true low wall edges and seam floor are measured. Quality parameters from the sampling of exposed coal (moisture, loss, and dilution).	Processing of ROM moisture content usually greater than in-situ moisture content. The values of loss and dilution thickness are determined based on a back-calculation of previous mining supported by detailed surveys of mining operations. Issues to consider in estimating loss and dilution thickness are over-cleaning possibilities, coal left behind, mining equipment used and blasting leading to loss and dilution, wet working areas will tend to increase both loss and dilution.	Comparison of ROM production to grade control model. This measures the efficiency of the mining process. Comparison of ROM ash to In-situ ash. Determination of apparent mining recovery (Compares ROM tonnes to In-situ tonnes.	Tracking and reconciliation packages such as QMASTOR and Mine Track have been identified. These are used to capture production data. Systems are capable of acquiring, validating and reporting production data needed to perform reconciliations required for reserve to customer optimisation.
MP3 - Feed tonnes delivered to the plant	Feed tonnage and quality. These include mine stockpile surveys, coal concentrations, delivered to plant and not immediately fed into the plant, truck tallies, weighbridge and conveyer scale readings. Truck tallies are compared with weighbridge readings. High-quality weight meter, moisture gauge, ash gauge and automatic mechanical samplers are required to monitor plant feed. The	Volumes are calculated based on mine's standard and software program. Variance in volumes should not exceed 5%. Analyses performed should include ash, moisture, size, washability by size, coking properties and contaminants. Consider monthly processing plans and weekly processing schedules. All protocols to be observed (for example the toll washing agreements, delivery protocols, BHP	Comparison of plant feed to grade control model. Properties of plant feed in the grade control model are compared with the properties of the plant feed to assess the suitability of assumptions and	Development of coal tracking and stockpile management systems

	following parameters must be considered for all ROM sources. Volume/mass of ROM coal, level of foreign material in the ROM coal, moisture, ash, CV and size.	Billiton Energy Coal South Africa (BECSA) and Anglo's coal agreements). Ensure there is no mixing up of coal from different sources.	adjustment factors used to generate GCM estimates. Dilution included during mining coal and actual mining recovery are also compared with GCM estimates.	
MP4 - Coal product	Coal product tonnage and quality. Accurate measurements of coarse plant reject, moisture and ash content are required to interpret plant performance. Parameters required for accounting purposes are mass, yield, ash, CV and size.	The moisture content of washed coal is greater than the ROM coal. Processing of washabilities, ash, CV and inherent moisture should be in accordance with existing sampling and analysis protocols. Consider rotary breaker losses, processing of feed coal quality should be described in terms of washabilities of the source coals and dilution materials inappropriate size fractions. Other considerations are processing preparation plant yield and blended feed and product quality.	Reconciliation between plant product and plant feed. This provides a measure of the efficiency of the coal washing process. All existing protocols should be adhered to.	All protocols to be observed. For e.g. the weighing protocols of the BECSA- Anglo agreement requires the product coal and discards to be weighed according to minimum specifications on a daily basis.

MP5 - Coal sales tonnage	Coal sales tonnage at the market points. Accurate tonnage is required to guide the reconciliation of coal production and the creation of coal parcels for sale. Transportation protocol of coal must be adhered to. Measurements are required for calculating clean coal volumes at silos and stockpiles. Coal from different sources is not to be mixed and coal for different purposes such as domestic and export are also not missed.	Sampling and analysis protocols to be followed. For e.g. BECSA - Anglo agreement requires analyses to be performed on coal products on trains. These include export coal trains, CV, total moisture and sulphur, domestic coal trains, CV, total moisture, sulphur, abrasive index, and sizing.	Comparison of coal sold to marketable reserves. Includes coal produced and sold for in a giving mining area. This also validates the assumptions used to estimate the marketable reserves.	Apply existing protocols for e.g. the phola plant must prepare a reconciliation report at the end of every month with the following: Comparison of ROM coal versus throughput. Reconciliation of metallurgical balance, Reconciling ROM coal with clean coal, Reconciling predicted with actual yields, reconciling losses with discard materials and explaining deviations and investigating losses.

Source: Tetteh and Cawood (2017)

2.7 Measurement of metal Content

To determine the metal content of material bearing metal along the flow requires a safe and systematic method to ensure none or minimum metal losses. Janisch (1973) defined ore accounting as a systematic approach for recording and representing ore valuation, mine grade and ore treatment statistics of a producing mine. The translation of physical metal losses into monetary values places an emphasis on areas with the greatest monetary losses (Storrar, 1981). This should enable management to focus on these specific areas for further improvement.

2.7.1 Sampling and errors

Sampling is done at various phases of mineral development. Sampling during exploration, face sampling in mining, plant/metallurgical/smelter sampling, laboratory sampling in precious/base metals, and bulk commodities. According to Minnitt (2014), South Africa's reliance on the minerals industry has compelled the industry to improve upon sampling practices. Many standards have been applied by the industry worldwide. Some of these are the International Organization for Standardization (ISO) used mainly by the bulk commodity producers to meet customer specifications whereas Gy's sampling perceptions are mostly applied by the precious and base metal producers who supply products to metal markets (Minnitt, 2014). Esbensen (2003) explained that Gy's (1979; 1982; and 2003) theory of sampling was the subject of discussion at the first World's Conference of Sampling and Blending (WCSB) held in Denmark in 2003. The seventh World Conference of Sampling and Blending was held in France in 2015. These conferences are held every second year, with the eighth

WCSB held in 2017 at Perth, Australia and the ninth WCSB held in 2019 in Beijing, China.

The main aim of every sampling process is to ensure that each sample is representative of the whole from which it comes from. Storrar (1981) described this concept based on the sample's size, spacing and the relationship between the gross mass of a sample to the parent ore body. Although in reality, it is nearly impossible to obtain a representative sample due to the processes the sample undergoes, there are various classifications of errors sustained by the sample along with these processes identified by Gy (1992 and 2003) and Pitard (1993). These errors are technically termed as Total Sampling Error. The nature of these errors and their sources are described in Table 2.4.

Table 2.4 Total sampling error description

Classification of the sampling errors in regard to material characteristics, plant processes, equipment for sampling and analytical procedures		
Total Sampling Error	**Source of error**	**Nature of error**
	Material characterization (sampling uncertainties)	In-situ Nugget Effect (INE): This is a function of the amount and distribution of nuggets in the host rock which is to be sampled.
		Fundamental Sampling Error (FSE) relates with the compositional heterogeneity as a result of the material properties of the lot.
		Group and Segregation Error (GSE) relates with the distributional heterogeneity as a result of the grouping and segregation in the lot
	Equipment for sampling and materials handling (Sampling errors)	Increment Delimitation Error (IDE or DE): This occurs when the geometry of outlined increment is

		not completely recovered; This can however be eliminated.
		Increment Extraction Error (IEE or EE), Material extracted does not coincide with the delineated increment; it can be completely eliminated.
		Increment Preparation Error (IPE or PE), All sources of non-stochastic variation after extraction of the material; error should always be nil.
		Increment Weighing Error (IWE or WE), may be relevant or not, depending on a specific context.
	Processes and procedures in the plant (A combination of sampling errors and uncertainties)	Short-range Process Integration Error (PIE1).
		Long-range (PIE1).
		Periodic (PIE3). Random time and cyclical fluctuations, usually subdivided into random and non-random effects.
	Analytical processes (sampling errors)	Analytical Error (AE), All sources of error associated with materials handling and processes in the laboratory.

Source: Adapted from (Minnitt 2014) based on Gy (1992, 2003), Pitard (1993, 2009)

In the scope of this research, errors that would be incurred under-sampling activities from mining face to plant entry are GSE, IDE, IEE, IPE, IWE and AE (errors are explained in Table 2.4 above). The impact of sampling error in gold mining operations from in-situ to plant entry is summarised in Table 2.5.

Table 2.5 Sampling in the gold mining industry from in-situ to plant entry

Face sampling phase and problems arising out of that phase	Error/ Impact
Face Sampling in mine grade control. Well-developed face sampling protocols. In-situ sampling has a great potential to reduce value. The Life of mine plans are based on in-situ sampling. Any bias at this stage can affect long term forecasting and life of the mine plan. Large pebble conglomerate reefs Ventersdorp Contact Reef (VCR) are easier to sample low MCF. VCR generally has a higher MCF than thin carbon base reefs. Some reefs are thin, composite conglomerate-carbon reefs (Basal, Vaal, and Carbon Leader). Each component has very different sampling characteristics. The tonnage calculation could be affected.	FSE, IDE, IEE Extremely high depending on the mining method

Source: Minnitt (2010)

According to Minnitt (2014), the combined error as well as bias is less in terms of severity for the wider reefs (VCR and Main Reef), compared to the narrow composite reefs made up of (Carbon Leader, Basal Reef, and Vaal Reef) of the Wits basin. Minnitt (2014) further explained that the narrow composite reefs contain small pebble conglomerates of 10 – 20 cm wide, a carbon-rich layer of 0.1-2cm at the base of the reef. The carbon soft layer may contain approximately 90% of the gold mineralization and therefore may result in a 20% overstatement of sampling values which has been the main contributor of low mine call factors and apparent gold losses (Minnitt, 2014). This problem was first anticipated and warned by Sichel (1947) and subsequently Harrison (1952). Cawood (2003) suggested that due to the use of accumulating units (for e.g. cmg/t), different densities should be applied to different reef widths. Lerm (1994) and Minnitt (2010) all agreed that an unchanging sample value is nearly impossible, even when different samplers have undergone a well-supervised sampling training program. Despite various attempts to overcome this problem of sample overstatement, Lerm (1994), observed that no progress had been made in this regard with the use of a single or multiple blade diamond saw. Cawood (2003) later emphasised a growing concern to obtain a mechanical tool that can obtain a faultless sample at an even depth in an efficient and economic manner. An example is the mechanised sampling tool, tried in the past like the former Chamber of Mines Research Organisation (COMRO) gold analyser which will be discussed in the third chapter. COMRO is now Minerals Council of South Africa.

2.7.2 Sampling practices in South African mining and minerals industry

Face sampling in South African gold mining operations is based on grade control procedures that rely on chip sampling of mineralized rock faces. Samplers and surveyors are trained to conduct stope sampling. Certificates demonstrating competence after training in this area are issued by the former chamber of mines, mining companies or technical colleges. Apparent losses as discussed previously occur during resource estimation. An example is ore misclassification which may occur during the ore body modeling process. In this aspect, Minnitt (2013) explored the potential of financial losses that may arise from grade distributions and poor sampling practices for three different commodities (gold, iron ore and coal). He realised that the effects of errors and bias on gold deposits are less significant when compared with iron ore and coal deposits. This was because a small error or bias affect the value of iron ore and coal deposit less than compared to e.g. gold.

The history of the practice of sampling in the South African minerals industry is extensively discussed by Minnitt (2010, 2014). Although there are many other classes of samples including bulk, groove, chip, grab and bore-hole sampling discussed by Storrar (1981: 24), face sampling on the Witwatersrand gold reef was investigated and documented by Cawood (2003) based on his experience. This is further combined with a literature review from various authors (Hoover 1933; Beringer, 1938; Jackson, 1946; Sichel, 1947a, 1947b; Harrisson, 1952; Krige, 1952, 1964, 1994; Rowland and Sichel 1960; Rowland, 1966, Storrar, 1981; Lerm, 1994).

Many mining companies, however, in recent times have developed their own standard operating procedures (SOP) for sampling. An example is a checklist developed for correct sampling practice in gold mining by Spangenberg (2012) and the internal underground chip sample standard developed by (Flitton *et al.*, 2009).

2.7.3 Mass measurements

The aim of the measurement of mass in metal accounting is to determine the mass of a material at any defined time or mass of the material flow over a specific time period at a suitable accuracy for the purpose of mass and metal balancing. The mass measurements are grouped into (JKMRC, 2008: 78):

- Measurements essential for custody transfer and primary metal accounting. An example is the measurement required for input and output streams to plant operation. A high-quality standard measurement is required here;
- Measurement required for the secondary metal accounting is for management control. This includes internal company transfers and plant performance. It

may be used for the purpose of cross-checking primary accounting. Environmental monitoring measurements also falls under this group; and

- Measurement for the control of the plant.

According to JKMRC (2008), mass measurement required for metal accounting is strict compared to other classes. This is because it requires certified weighing equipment and the creation of a random error model associated with the mass measurement.

2.7.4 Density, moisture and tonnage measurements

Lipton and Horton (2014) classified density into four different categories namely Specific gravity[9], Density[10] , In-situ bulk density[11] (ISBD) and Dry bulk density [12](DBD). Although density is defined in different terms, it is measured by laboratory tests whereby the mass of a substance is accurately determined and weighed on an electronic balance. Even though volume determination is based on several methods, AMIRA (2007) proposed the simplest method is through the displacement of the liquid method. An appropriate way of measuring moisture content and dry mass is in a laboratory setting where the weight of samples of bulk ore is measured on an electronic balance and later dried under well-defined conditions in an oven over a specific time period to obtain the dry mass and moisture content. The loss in weight can then be calculated. According to Wortley (2009), an error of 1% in the moisture value, will result in a mass measurement that will be in an error of 1% (either low or high of the

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[9] Specific gravity also known as relative density is the ratio of the density of the material to the density of water at 4°c (39.2 F). A fixed temperature is necessary because the density of water varies with change in temperature. Water at 4°C reaches its maximum density.
[10] Density is defined as the mass per unit volume and measured in t/m^3.
[11] In-situ bulk density is the density of the material at natural moisture content. The unit is t/m^3.
[12] Dry bulk density is used when the material is devoid of free moisture content. The unit is also t/m^3.

true value). For the purpose of this research, moisture content of ores which occurs before mined ore is grinded includes:

- Mine ore passes;
- Ore in bins/silos;
- Rom Stockpiles; and
- Primary feed stockpiles.

A challenging task, however, is how to ensure samples taken are representative of the whole. It is important no evaporation or water ingress occurs before samples are taken. Other technologies used in determining moisture content are the neutron or the micro gauges (Wortley, 2009). These technologies would be discussed in detail in the third chapter.

The degree of uncertainties associated with density measurements will directly impact on the mass. The dry mass is calculated from the volume of mined ore. Volume is however determined by the surveyor's measurement. Tonnages are calculated based on the density and volume of mined ore. According to Makhuva *et al* (2014), Anglo American identified ten different methods used for density determination outlined in Table 2.5. Anglo American Platinum operation uses two different methods for density determination namely the Helium gas pycnometer[13] (developed by Anglo American Technical Solutions Research in partnership with micrometrics) for pulp samples and the Hydrostatic immersion (also known as Archimedes method[14]) for drill cores.

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[13] The helium gas pycnometer measures the difference in pressure between an empty sample compartment and a pulp sample compartment. A change in pressure is then linked to the volume gas that is displaced.

[14] Archimedes method measures the difference in weight of a sample in air and water.

Table 2.6 Density measurements in Anglo American Operations

Method of density measurement	Business Units/Operations
Air-core drilling	Nickel
Gas pycnometer	Platinum, Kumba Iron Ore
Hydrostatic immersion (Archimedes)	Platinum, De Beers, Copper
Calliper	Niobium, de Beers, Phosphate, Iron Ore Brazil
Sand replacement	Iron Ore Brazil
Water displacement	De Beers, Iron Ore Brazil, Niobium
water displacement	Nickel
Metal box sample	Iron Ore Brazil
Weighing of the full core tray	Iron Ore Brazil
Coal relative density	Metallurgical Coal and Thermal Coal

Source: Makhuva *et al* (2014)

The two sets of methods are used on the same piece of half core samples and results are compared using a predefined tolerance level. As part of an internal Quality Assurance and Quality Control (QAQC) procedure, Anglo American Platinum employs standard reference materials to determine the accuracy and precision of both measurements. A duplicate immersion test is also conducted on at least 10% of all samples.

The method of density measurement is based on the physical characteristics of the ore body as well as practical conditions present at a specific site. From Table 2.6, five different methods are employed in determining density measurement in Iron ore producing operations. The calliper method for compact and semi-compact ore; Sand replacement for friable ore; Water displacement for compact ore (Makhuva et al, 2014).

Kumba Iron Ore, however, identified some limitations with regards to the pycnometer which utilises milled material (Makhuva *et al.,* 2014). This implies that the physical characteristics of the iron ore (for e.g. porosity) may be missed when determining bulk density (Makhuva *et al.,* 2014). Kumba iron considered a pycnometer which is able to analyse complete rock or core sample (Makhuva *et al.*, 2014). The Archimedes method is used in the copper operation. The apparatus, procedure and calculation of rock density (BS:812[15]) obtained from an unpublished document from the geological engineering laboratory of the University of Mines and Technology (UMAT) are outlined in subsequent subsections.

2.7.5 Apparatus for density measurements

The instruments required for a simple density test include waxing pot and ladle, electronic balance, thread, hammer, beaker, distilled water, paraffin, wax, and an oven (UMAT, 2014).

2.7.6 Procedure for density measurement

This procedure for density calculation is adapted from (UMAT, 2014). The rock core is broken into pieces (usually weighing between 80 to 150g). For each sample given, three specimens are prepared for the density test and an extra three for the moisture content test. The weight of specimens are determined on an electronic balance to the nearest 0.01g. Specimens for moisture content are put in the oven for at least 20hours. Paraffin wax is then applied to density specimens to prevent water absorption and then weighed. A beaker containing 2/3 full of distilled water is placed on an electronic balance and weighed. The weight of the balance should be tarred to 0.00g. A piece of

[15] British Standard: 812

thread is tied around a specimen and gently lowered into the beaker until it has fully submerged. Precaution should be taken to prevent the submerged specimen from touching the beaker. The reading on the electronic balance is then taken. The oven-dried specimens are removed after 20 hours, cooled in a desiccator and weighed.

2.7.7 Archimedes method of density calculation

The Archimedes method of density calculation is adapted from (UMAT, 2014).

The density of paraffin wax is 911 kg/m^3 and water is 1g/cm^3.

Mass of rock specimen = M1 g

Mass of waxed specimen = M2 g

Mass of displaced water = M3 g

The density of water is 1g/cm^3 and the mass of displaced water = volume of waxed sample.

The volume of waxed sample = M3cm3

Mass of wax = M2-M1

The volume of wax = M2 – M1/0.911

Volume of specimen, V = M3 – (M2-M1/0.911) cm3

Bulk density (ρb) = M1/V tonnes /m3

Mass of moisture content = (Mass of wet sample-Mass of the dry sample)/ (Mass of the dry sample)* 100%

Dry density of rock = (100 ρb)/ (100+w)

2.7.8 Quality assurance and quality control (QAQC) procedures

According to Makhuva *et al* (2014), Anglo American uses a second laboratory to verify original measurements as part of quality control measures. The three methods regularly used at De beers are the Archimedes, callipers and water displacement (Makhuva *et al.,* 2014). Due to the physical characteristics of kimberlite which is usually porous and easily breakable, samples are coated with an exterior durable finishing. As a quality control measure, a different method is used to check the quality of original measurements (Makhuva *et al.,* 2014).

Niobium and phosphate operations use the calliper method to determine densities (Makhuva *et al,*. 2014). As a quality control measure, 5% of samples are measured and cross-validated. using the water displacement method.

Anglo American nickel operation determines density using the water displacement method and phosphate operations use the calliper method to determine densities (Makhuva et al, 2014). 5% of samples are measured again and cross-validated using the water displacement method (Makhuva *et al.,* 2014).

Several QAQC procedures and analysis wasr outlined by Tetteh (2014), for a gold mining operation.

The author recognizes that some of the biggest sources of errors arise from the mass and volume determination of stockpile ores. Wortley (2009) identified four problem areas that contribute to inaccurate mass measurements for metal balancing. These are the design and selection of appropriate measuring equipment, calibration and certification of equipment, good record keeping and good housekeeping and management (Wortley, 2009). Some technologies that have been used for density measurements include the ultrasonic level detectors and nuclear (gamma) meters (Wortley, 2009). These technologies will be discussed in the third chapter.

2.7.9 Accuracy and precision

The terms accuracy and precision have been used interchangeably in the past but are not the same. Accurate measurements have the average of a number of the same measurements that are close to the true value (which is usually unknown). Precise measurements, have a standard deviation about their mean value lower than a defined probability density distribution (JKMRC, 2008). An illustration of accurate and precise measurements is in Figure 2.6. In the squares numbered 1, 2 and 4, measurements are either closely related or scattered with a standard deviation which is far from the central tendency point unlike the measurements found in cell number 3 whose standard deviation is within the central tendency. The aim of every measurement is to obtain an accurate measurement. It can be inferred from Figure 2.6, that accuracy determines the validity of a measurement, whereas precision determines the reliability of a measurement.

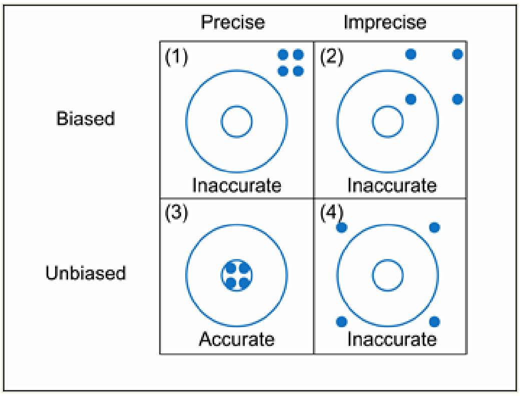

Figure 2.6 Accuracy and Precision (Source: Adapted from Statistics How to , 2019)

2.8 Assessment of blast fragmentation

The blast fragmentation (must be accurate) is essential to enhance productivity in mines since the fragmentation parameter informs the type of mechanical equipment employed for the loading and hauling purposes. There are currently two methods known to be used to assess fragmentation (Marton et al., 2000). These are semi-quantitative and qualitative approaches. Marton *et al* (2000), further explained that the use of cameras to capture photographs of the blasted muckpile of a certain period describes the semi-quantitative whereas the qualitative approach involves video filming, photos and observations.

Traditionally, blast fragmentation distribution has been measured and monitored through a physical sieving process and/or visual inspection. The size of these fragments, however, varies between large boulders and small fines.

To determine the fragmentation distribution Fourie and Zaniewski (2005) suggested that a representative sample first has to be obtained. The manual loading of samples is unlikely because it cannot guarantee sample representativity. After several considerations, a sample size of $1m^3$ was selected using a steel designed pan placed against the face prior to blasting and fitted with a means of withdrawing to the back area after blast (Fourie and Zaniewski, 2005). The content is then removed and transported onto the surface for analytical processes.

The crux of the issue is the workload and processes involved in obtaining a representative sample, transporting it in a way that prevents contamination, and finally transporting it to the laboratory for analysis is labor exhaustive and time-consuming. As much as it disrupts the production cycle, it also translates in production cost as well as the time it takes for the results of the analysis to be out. Several attempts have been made by the research community to develop the Digital Image Analysis Technique (DIAT) used to determine fragmentation distribution. These technologies and software will be discussed in detail in the third chapter.

2.9 Ore dilution and monitoring

Variogram models and kriging are geostatistical tools widely used for spatial prediction and modeling. The term Geostatistics was first proposed by Matheron (1960) to determine the distribution of values in space, for e.g. ore grades and thickness. Models for these values are then created and used in ore valuation. In South Africa, Krige (1966) applied mathematical statistics to the valuation of ore reserves. The basic principle in geostatistics is that spatially distributed variables are interrelated to each other and exist as random variables. The modeling process incurs dilution and ore loss.

Dilution and ore loss impact directly on the cost of production and mining revenues. An important aspect of the Ore Reserve estimates or mine scheduling is with the correct modeling of the ore body to enable an appreciable amount of the ore dilution and ore loss. There are various methods used in the estimation of ore dilution and ore loss carried out in computer block models. The inherent variability in the geometry of ore bodies is a common thing and challenging to geologically interpret particularly when the ore body is irregularly shaped. These would fall within apparent losses which occur during estimation and modeling processes.

2.10 Statistical methods and analysis

Several statistical methods are applied in analytical laboratories. Examples are the analysis of variance (ANOVA) method and the method of applying the student's t-test for comparing results from two analysts and the method of calculating precision. The procedure which is commonly applied is the "Shewhart Control graphs" and cumulative sum (CUSUM) graphs (JKMRC, 2008:198) which is discussed subsequently.

2.10.1 Shewhart's control graph

This Shewhart control graph is used commonly to analyse measurements in quality control or certified reference material (also known as standard reference material). The steps in making these graphs are (JKMRC, 2008:198):

- The accepted value (best value) of the measurement is fixed at the origin of the y-axis;
- x-axis is divided into integers to indicate the sequence of the analysis which in most cases is the date;
- Draw parallel horizontal lines above or below the x-axis at values of ±2 x standard deviations (SD) called "controlled limits" and ±3 x standard deviations (SD) also called "action limits";
- The measured values are then plotted on the graph;
- Any result outside the control limit (±2 SD) should be reanalysed and result outside the action limit (± 3SD) is an indication of a major problem which should be immediately investigated; and
- If a series of more than 5 sequential results are above or below the x-axis, there is a possibility of a biased situation.

2.10.2 Cumulative sum graphs

CUSUM graphs are used to monitor possible bias in analysed values of a quality control. The steps for plotting CUSUM graphs are (JKMRC, 2008: 200):

- The origin on the y-axis is set at the accepted value of the measurement and the x-axis is divided into integers to represent the sequence of the analysis or the date;
- The assigned value is subtracted from the measurement and the difference is plotted at an appropriate point on the graph;
- The subsequent differences are plotted in relation to the last point; and
- A resulting series of positive values indicate a positive bias and the negative values indicate a negative bias

The formula for calculating Bias is given as:

[(Mean of received results/expected value)-1] %.

2.11 Investigating discrepancies

The MCF issues are numerous and present difficulty in determining the exact causes of discrepancies. Most of the factors to consider have been discussed in the previous section. However, a seven-step approach to conducting an MCF investigation was outlined by Cawood (2003) and depicted in Figure 2.7. A notable point here is that MCF investigation is likely to be successful when initiated and supported by management due to operational interventions and resources that are usually required to undertake such investigations. This philosophy behind an MCF investigation approach in Figure 2.7 is indicated by a triangle that widens upwards and narrows at the bottom because the scale of work reduces as one goes through the steps of the investigation.

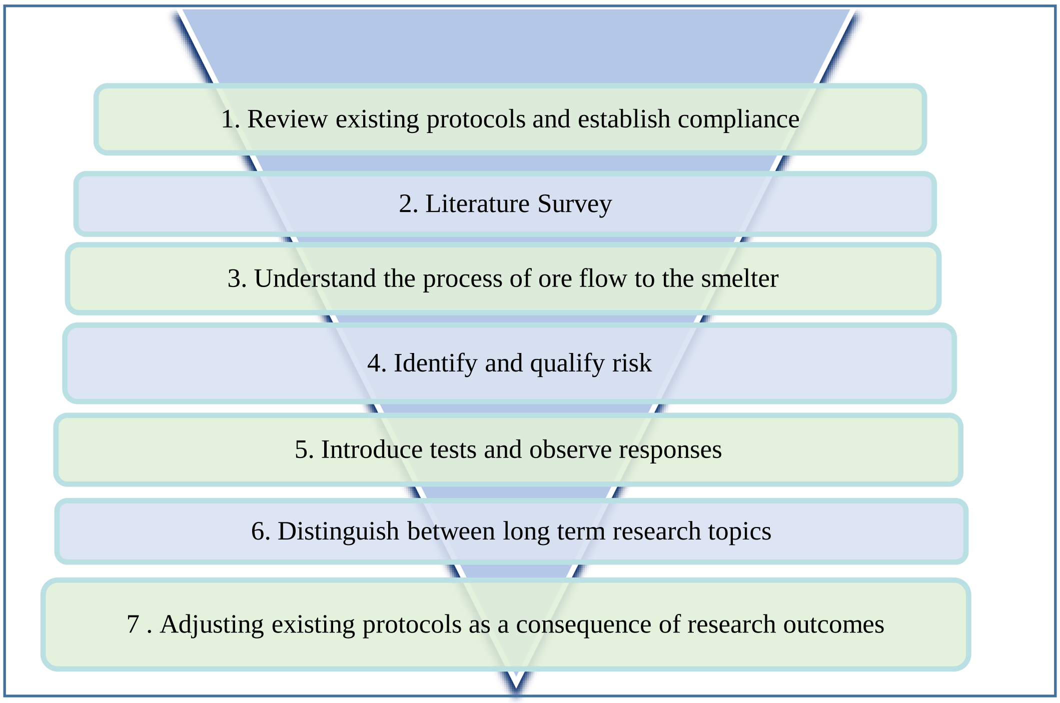

Figure 2.7 MCF investigation approach (Sources: Tetteh and Cawood, 2014; updated from Cawood (2007))

Each of these steps is explained by Cawood (2003). The first step is to "review existing protocols and establish compliance". The initial step is crucial and time-consuming because it entails a complete review of all existing protocols (evaluation, drilling and blasting, mining, sweeping and cleaning cycles, grade control, assay protocols etc.) and comparing it with best practices. This is because there is no reason for pursuing an MCF investigation if there is non-compliance with mine protocols in the first place. The various components of an MCF are necessary to consider here.

Step 2 is a literature survey which involves gathering information on previous investigations on the mine or other related mines. The idea here is not to re-invent the wheel but to study solutions that may have been applied previously to similar problems at similar operations.

Step 3 is a detailed understanding of the ore flow process, which begins from the point ore is broken at the face to the point where the metal/commodity is formed. This process is revealed in a metal content sheet which reflects the estimate of metal content at various points of measurements along with the ore flow (Refer to Table 2.1).

Step 4 requires identifying and quantifying risks. The use of flow sheets is instrumental in identifying various risk parameters. Although a standard flow sheet is illustrated in Storrar (1981), a flow sheet is specific to a particular mine. The magnitude of each risk parameter is determined using sensitivity analysis. For instance, in South Africa, a study on sampling narrow reefs of the Wits gold has revealed that a 1% decrease in sampling value would result in a 1% increase in MCF (Cawood, 2003).

The 5th step is to rank the risk variables according to their magnitude of risks based on sensitivity analysis in step 4. High and low-risk variables will be tested and therefore interruptions with current protocols may be carefully planned, executed and scrutinised, after which results are scientifically analysed.

The 6th step is to distinguish between long and short term topics. When the tests introduced in the 5th step give justifiable reasons to question existing protocols, then there is a case for further research. It is advisable for such research to be conducted through independent institutions or employees from the mine who can do research for a higher degree as part of their career development plan.

2.12 The implementation model for ore tracking in the digital mine

The purpose of measuring the production process is to provide adequate and accurate information that explains quality and quantity along the value chain to enable better resource models and ore accounting.

International strategies carried out in recent times include the Centric Inventory Manager (CIM) which provides ore tracking, stockpile management and model reconciliation (Centric mining systems, 2017). Through an integration of various systems and processes, the CIM is able to provide visibility of grade control, ore movements, stockpile and feed through the processing plant and customers. According to the centric mining system website, the mine block depletion, dilution, stockpile balances, ore movements, and processing feed are visible in near real-time. The CIM enables every transaction to be fully auditable and used to maintain an accurate picture of in-situ blocks, broken material, mining and processing materials as well as customer shipments.

Another system developed in Australia for tracking ore is the SmartTag system developed by Metso's process technology and innovation (PTI) business unit. The system enables spatially based ore characteristics such as fragmentation, mineral content and ore hardness, to be linked with time-based performance in the processing plant (Creamer media mining weekly, nd). The SmartTag system enables the tracking and the correlation of the ore characteristics and quality with important operating parameters in the mine such as fragmentation, dilution, stockpile residence times. Although it was developed in 2004 in Brisbane Australia, the first major application of the system was in Chile in 2006. By 2010, the application of the SmartTag system was in the United States, South Africa, Peru, Brazil, Chile and Australia (Creamer media mining weekly, nd).

For the purpose of a digital mine, real-time monitoring of broken ore variables (volume, mass, density, grade, and fragmentation) will enable real-time communication of possible physical losses through a two-way communication path from in-situ to plant entry. Communication of possible losses will then be received through an alert system in a control room which houses the production management technology system which may be perceived as the data warehouse. Figure 2.8 is an implementation model for tracking broken ore variables for a digital mine. The first step is to establish a data warehouse that will contain the truth about the measurement variables. Once the database is properly set up, it becomes possible to apply big data[16] concepts to MCF issues. Several opportunities arising out of a single data warehouse are, generating of reports and reconciliation, MCF data where losses can be determined through an alert system, and analysis and proactive decisions can be taken. In a nutshell, less time is spent on searching for data and proactive decisions can, therefore, be made.

[16] Big data analytics is the process of investigating large data sets which are usually of various data types for the purpose of determining hidden patterns, market trends, unknown correlations, customer preferences and useful business information (Search business analytics, 2019)

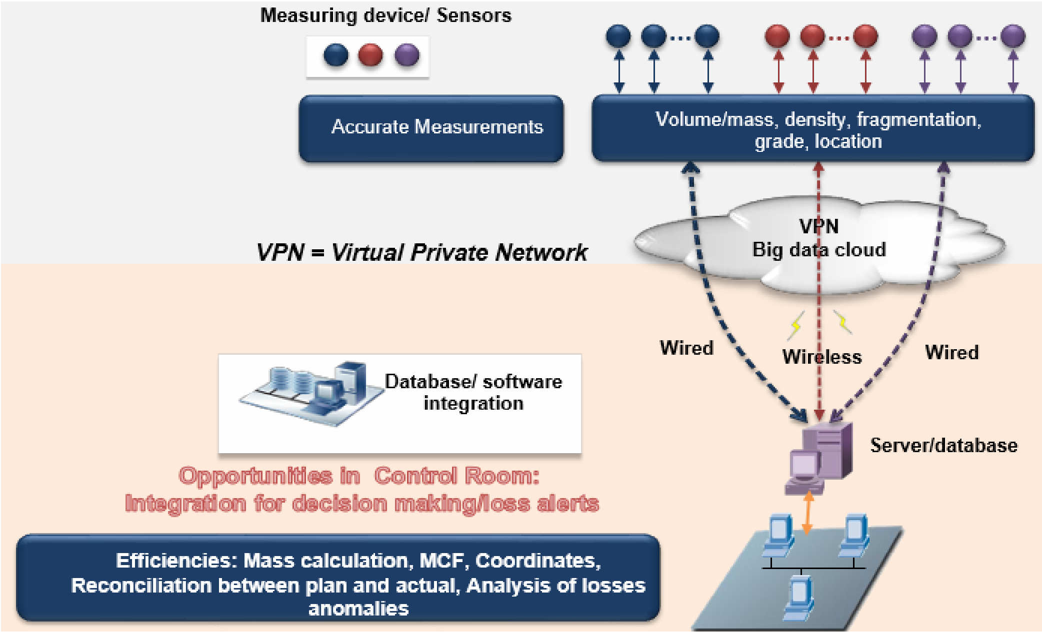

Figure 2.8 Implementation model for ore tracking (Source: Researcher's concept adapted from, DigiMine, 2016)

2.13 Conclusion

The theory of MCF cuts across various technical disciplines, ranging from resource estimation, mine planning processes and reconciliation between actual and planned, mining and processing stream, and the measurement of various broken ore variables.

A scientific approach for conducting an MCF investigation was developed by Cawood (2003) by analysing some variable components suggested by Storrar (1981), at the time. A finding of the MCF investigation conducted by De Jager (1997) in Western holdings mine was to question the accuracy of grade estimation. Tetteh and Cawood (2014) also investigated some variable components of the MCF from a surface mine perspective.

Although a standard operating procedure for sampling practices is extensively documented by Minnitt (2010, 2013, 2014) who described the various aspects of the total sampling errors based on Gy's sampling program, the author perceives that many mining companies preferred to develop their own procedures for sampling practices.

The measurement of broken ore characteristics/variables which influence the MCF includes the mass, density, moisture content, fragmentation measurements as well as ore dilution and ore loss determination procedures. The aim of every measurement, however, is to obtain an accurate measurement. Various statistical tools such as the Shewhart control graph and cumulative sum graphs are used to determine the accuracy of measurements over time.

The mine planning and reconciliation process in coal mining are often filled with discrepancies that cannot be accounted for. Although a standard operating procedure is required for all these measurements of broken ore based on standard operating procedures at each critical measurement point, the author opines that the ability to effectively track and monitor these ore variables with georeferenced technologies throughout the production chain could lead to the possible determination of physical ore losses to enable proactive decisions and preventive measures to be made.

An implementation model for design considerations for digital mine is discussed. A single truth is established in a data warehouse in a control room where opportunities for generating reconciliation reports, communication of losses through an alert system and proactive decisions and analysis can be made. This chapter also proposes the possibility of applying big data analytics as a possible solution to the concepts of MCF issues.

The third chapter is a documentation of sensor technologies and measuring devices that have been used to measure broken ore characteristics and some new ones to be used. The amount of production time saved since the implementation of these technologies will be discussed in some cases.

3 Material monitoring and tracking technology options

3.1 Introduction

Throughout the LoM, all stakeholders require accurate information. This information is then preferably represented in visual form. Woodhall and Strydom (2010) asserted that real-time spatial visualization of fully integrated technical data-sets is important. These integrated data sets improve information management throughout all stages of the LoM and enable business alternatives to be properly analysed.

To date, several technologies were tested in the mines for different purposes. Some of these technologies are Radio Frequency Identification (RFID), which was used mainly in the asset tracking industry. Laser technologies are used to measure the as-built of working areas to determine the rate of mining and volumes of materials mined. The use of video analytics to determine the movement of humans, materials and fragmentation in real-time is also not a new concept. Aerial photogrammetry for stockpile measurements and management is also well known. This chapter highlights some of these known technologies and the microdot technology used in car tracking which will be tested in this thesis.

3.2 Tracking technologies

The real-time satellite tracking of material throughout the value chain is an ideal solution for tracking metal content. Although this option is currently not available, several tracking technologies are employed in the tracking of material characteristics (location of ore parcels, fragmentation, density, content, moisture content, etc.) throughout the production process. Some of these technologies will be discussed subsequently.

3.2.1 Radio Frequency Identification technology

The tracking of ore was traditionally made possible using a number of manual innovations (washers, metal balls, and wooden blocks). In recent times, RFID technology has been applied mainly in the asset tracking industry. The technology was used in mining for proximity detection systems to alert miners of the presence of static and moving equipment within their vicinity. For example, tracking explosive initiators (for security purposes) and tracking ore and waste parcels. Several pilot projects have taken place in South Africa, Australia, and South America. A South African example of the technology is the Oretrak system provided by RF tags South Africa. It is used to prevent cross tramming (misrouting of ore where waste is sent to ore and vice versa). However once ore from various sources underground is tipped into the ore pass, it is difficult to link it back to its original face.

According to the RF tags SA website[17], RFID tags come in three different variations and frequencies with 128 kHz, 13.56 MHz, 868 MHz, and 915 MHz being the common ones. The Active RFID Tag has its own internal power source (with a maximum battery life of ten years) which powers the circuits and used to generate radio frequency (RF tag SA website). Active RFID is generally the most expensive tag but their tag readers are relatively cheap. The passive tags require no internal power source and are unable to self-generate radio frequency (RF) signals. The RF readers power them when they come into their range of a distance of 10cm to several meters. The last variation of RF tag is the Semi-passive RF tag, which is similar to the active one because it has its own internal power source. However, the semi-passive RF tags don't generate RF

[17] http://www.rftags.co.za/rfid-technology/types-of-rfid-tags.php

signals as in the case of the active ones. They reflect the signal received from the RFID reader and back to the reader.

Research conducted by (JKMRC, 2008) demonstrated the use of RFID technology to track ore parcels throughout the mining process. Ore material is tagged at its source using markers representing volumes of ore or waste and later detected as it flows through the system, or not detected if it goes to the waste dump. In cases where tagged material is sent to a long-term stockpile, it can later on be detected when it is processed and then reconciled back to its source (Figure 3.1).

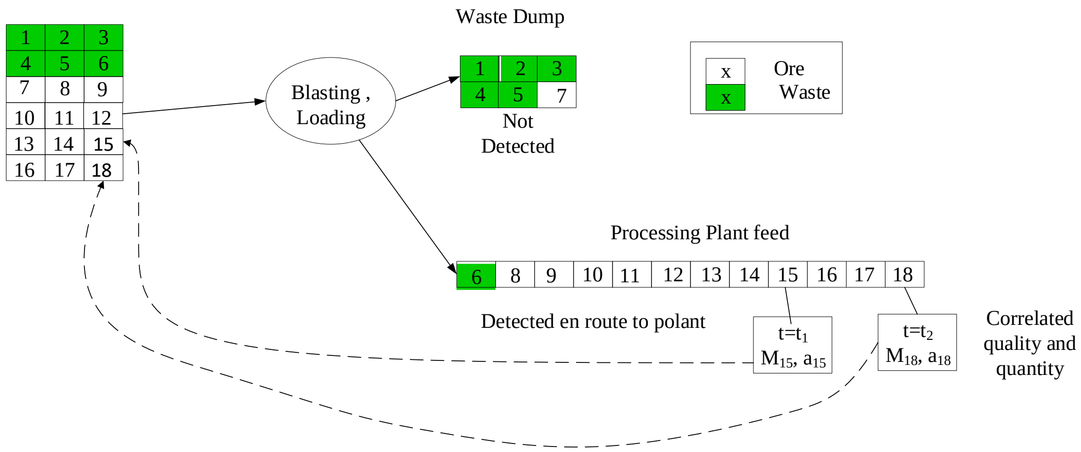

Figure 3.1 Tracking ore parcels from source to destination (Source : Adapted from JKMRC, 2008:445)

Kumba resources, which is now Kumba iron ore and Saco systems in South Africa, demonstrated the use of RF tracers in the mining industry for iron ore tracking and blending (Fouche, 2005). The project was conducted in both underground (Rosh Pinah[18]) and surface (Thabazimbi[19]) mines. The results showed that 10% of tracers survived the blast when installed before blast. In the opencast blasts, only 3% survived,

[18] Lead and zinc mine located in the southwestern part of Namibia.
[19] Located in an iron-mining town in Limpopo of South Africa.

out of which 100% survived loading and 63% survived primary crushing. This implies that a different technology is required between the rock face and fragmented material after blast. Although the survival rate of RF tracers was higher in underground mines than for open cast tests, the survival rates of these tracers were generally low. The RFID tag system developed by the ore track South Africa was also used on Phakisa mine to address the problem of determining the correct feed of ore and dilution factor because the waste and ore reefs were being transported on the same conveyer belt (Reinders,2013). The total recovery for these tags was 100% over a period of above 31 days with approximately 70% of these tags being recovered within five days of issuing. Tags were issued at different levels in the mine. According to Reinders (2013), the Phakisa mine made significant profit from the use of the RFID tag system since expenses was decreased as fewer labour was needed to control the ore. From the previous discourse, it can be said that there was an improvement in the RFID tag system developed by the ore track SA over the one by Kumba resources and Saco systems. RF Tags SA PTY Ltd developed RFID tags and readers with associated software and communication components used in mining for the purpose of ore grade management, ore loss control, material flow and blast monitoring.

A case study conducted in Australia by Nozowa et al., (2009) demonstrated an improvement of the RF tag design to increase ore tracking from mine to mill. They realised that it was advantageous to use a material tracking system called SmartTags^{TM} (20mm sizes) designed by the Metso Processing Technology Innovation (MPTI) rather than normal size RFID tags (60mm sizes) because of their ability to survive harsh mining and processing conditions. MPTI used this material tracking system built around tough RFID transponders for ore tracking at a Newmont Ahafo project in the

Brong Ahafo region of Ghana during a Mine to Mill optimisation process exercise (Mwansa et al., nd).

3.2.2 Scanning technologies

High definition sensor instruments plus associated processing software have rapidly developed into one of the fastest, reliable and accurate surveying technologies. Although traditional survey instruments such as total stations are still required for positional surveys, laser-scanners have an advantage over traditional survey equipment because they do not require targets at the mining face, making remote surveying within an open pit and underground safer and possible by an individual. Various engineering professions including civil, the cinema industry, architectural design, mining, etc employed scanning technology for validating as-built situations like stockpile in the open-pit mines. It has widely been used in the survey industry, particularly in Google Maps™ whose concept can be transferred underground or on surfaces into a digital mine. Maptek's I-Site 8820 laser scanner recorded accurate and fast end of month measurements; accurate as-built and void volumes; useful for deformation monitoring; drill and blast hole clearance and optimization[20]. In Underground mining, 3D laser scanning technology was tried at one of Anglo-American Platinum's shaft (Thembelani 2) and proved to eliminate the need for regular visits to take detailed section updates as opposed to scan data (Van der Merwe and Andersen, 2013). They realised that although laser scans are far more expensive than total stations that are useful for establishing survey controls, they are able to capture more points in a short time (for e.g. 50 000 points per second at an average scan of 3.5

[20] Maptek Forge Newsletter, June 2016 edition, Pg. 6.

minutes). This is in contrast with a total station that will capture about 500 points in a shift for 4 hours. This, however, means that laser scanners have great potential to provide optimal and detailed spatial data however it is important to also emphasise that traditional survey equipment is still required for positional measurements. Table 3.1 outlines a list of companies involved in the development of digital technologies and their various functions in the area of mine surveying solutions, GIS visualization, geological services, mapping solutions, 3D mobile scanning solutions, Position surveys monitoring and remote sensing.

Table 3.1 Digital technologies and their functions

Digital Technologies	**Mine Surveying solutions and Mining**	**GIS solutions and visualization**	**Geological services**	**Mapping solutions**	**3D Mobile Scanning solutions**	**Position surveys and measurement**	**Monitioring**	**Remote sensing**
AAM Geomatics	*	*	*	*	*		*	
Aciel Geomatics		*		*	*	*		
Afgen	*	*		*	*		*	*
Afrigis		*		*	*		*	
Autobuild Africa	*				*	*		
C&C Technologies	*	*			*	*		
CAD Mapping	*	*			*	*		
Carlson Software				*		*		
CK Aerial Surveys		*			*		*	*
Data World		*		*				
Dhuva Spatial Solution		*		*	*			
Esri South Africa		*						
Geo Data Design		*		*				
GeoSpace International		*		*				*
GeoTerraImage		*		*				
IQLaser					*			*
Leica Geosystems	*	*		*	*	*	*	*
MapAfrika						*		*
Microsoft/Vexcel Imaging				*				*
Optron	*	*		*	*	*	*	
Protsurv Coastal and Protsurv Geo Centre						*		
Riegel Laser Measurement Systems				*	*			
RocketMine	*			*				
Seabed						*		
Sitech		*				*	*	
Southern Mapping	*	*	*	*	*			
Spatial Technologies		*	*	*				
Topcon Positioning				*		*	*	
Wooding Geospatial Solutions	*							

Source: Adapted from (Position IT, 2016)

3.2.3 Aerial Photogrammetry Survey

Aerial photogrammetry is a remote and safe method of data collection, useful for large surface operations and especially for areas with large elevation differences and areas that are difficult to access (for e.g. flood areas, underground working areas, coal stockpile, etc.). The method involves taking images of control points of known positions with specialised cameras. Regulations with regards to the commercial operation of remotely piloted aircraft systems (RPAS) in South Africa was first announced at a press conference by the Director of Civil Aviation Authority, on 17th May 2015 and was effective on 1st July 2015 (IMSSA communication, 2015).

In recent years, UAV's have been used in the mining industry for collection of geotechnical data[21], for pit and dump management, surface stability monitoring, as-built surfaces for drill and blast designs, stockpile management and general mapping of inaccessible inclines[22].

3.2.4 Microdots Technology

All measuring technologies discussed previously have either been used or tested or are currently being used in the mining industry. For the purpose of this thesis, a new technology to be tested for tracking metal content is the microdot technology, mainly used in asset and vehicle tracking.

[21]Annavarapu S and Kumar, G. P (2015), Development of drones to collect geotechnical data in Large underground mines. APCOM, 37, pp382-388. Fairbanks;
[22] Drones for Mining, Retrieved from senseFly.com:
https://www.sensefly.com/applications/mining.html and http://www.rocketmine.com/our-solutions/mining/

The Microdot technology (not visible to the naked eye) contains information that enables proof of ownership of assets by registered owners (MicrodotSA, 2014). This technology originated in the United States of America (USA) in the 1940's for the identification of items (DataDotDNA, nd). According to DatadotDNA (nd) website, the technology was first used in the casino industry to detect fake casino chips which were manufactured and gambled throughout the world. The technology is being used in the vehicle industry to mark vehicle parts with a unique identity (ID) number (Microdot SA, 2014). The numbers are only visible to the naked eye through a magnifying lens and ultraviolet (UV) or infrared (IR) sensor.

A commercial product in South Africa which uses a similar microdot concept known as the veridot system has been used in the mining industry to identify copper cathode and aluminium ingots which were transported in mines (Peterson, 2015). The veridot system comprises of a self-contained aerosol system and a pen marking system that can be applied anywhere at any time and does not require a power source. The product is made from nickel and able to withstand temperatures to a maximum of 1200°C. According to Cashdoller and Zlochower (1990), maximum explosion temperatures ranges from ~ 1270°C for tin and tungsten powders to ~ 2520°C for aluminium, magnesium and titanium powders. This implies that microdot would not be able to withstand explosives that generate heat exceeding 1200°C. Microdot (500 microns in size) that is contained in the pen or aerosol, bears a unique pin code that is unique to that specific pen or aerosol as indicated in Figure 3.2.

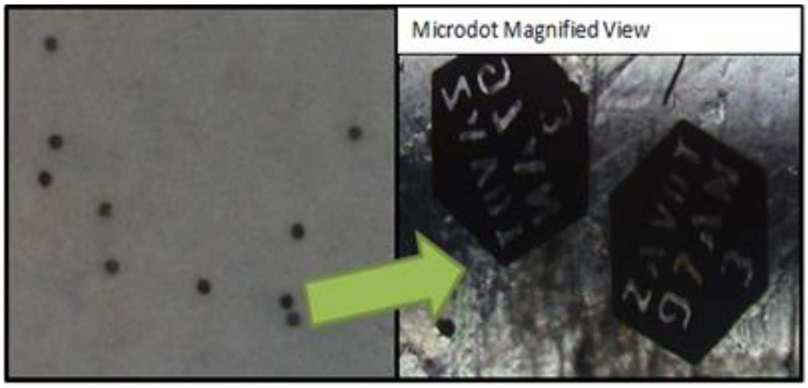

Figure 3.2 Microdot Structure with unique code (Source: Researcher, 2016)

It can be detected by a metal detector, magnifying glass or by a media containing ultra-violet or infra-red rays. The non-dependency on electrical supply makes the veridot product energy efficient for plant operations. Other qualities of the product according to Holomatrix (the main distributor of the product) are:

- The product is easy to use;
- The system uses a live internet-based management system to detect dots;
- It has been tested in explosives and known to retain its data integrity after blast; and
- The veridot system is an ISO 9001 manufactured product and SANS534-1 compliant product.

The heat generated from explosives in the mine and throughout the metallurgical process should however not exceed 1200°C for the microdot technology to survive. Through a conversation with Peterson (2015), it was mentioned that the technology has been tested at Kumba iron ore. In order to conduct an independent test, this research would test the suitability of microdots as a possible solution for ore tracking. The testing procedure and results would be discussed in the fifth (5^{th}) chapter

3.3 Technology options for fragmentation analysis

Accurate measurement of blast fragmentation is key to a successful mine to mill optimization process, which is a requirement for an increase in mine productivity and accurate mass calculation. This is because the fragmentation parameter has an impact on the efficiency of the mechanical equipment for loading and hauling. It also affects the density for converting volume into mass.

Traditionally, the method of using mesh sieving (which cannot be done without disrupting the production process and not reported in real-time) was used to measure the distribution of fragmentation sizes. In recent times, several DIAT systems have been developed for determining blast fragmentation and documented by Chakraborty et al, (2002) which includes Fragscan (France), WipFrag (Canada), Fragalyst (India), Tucips (Germany), CIAS and Split (USA), Power sieve (Australia), IPACs and KTH (Sweden), and gold size (USA and Canada).

The DIAT is acknowledged for determining blast fragmentation distributions resulting from blasting (Raina, 2013). According to Raina (2013), this method has been in existence for over 25 years and mainly classified into two groups namely:

- Static systems where images of blasted muckpiles are taken and examined after collecting post-blast images; and
- Dynamic systems also referred to as online systems in which cameras are fixed on conveyer belts and capture images of crusher fragmentation or plant feed sizes at fixed intervals.

Although the DIAT was well received by the industry, it is faced with a number of challenges arising from the method of assessing fragment sizes discussed by Cunningham (1996).

The use of photographic-based systems for particle size determination has been widely researched since the 1980's by Carlsson and Nyberg (1983), with various degrees of success. Some of these are discussed by Noy (2006) who agree that rock fragmentation measurements with digital photogrammetry has offered an improvement in the measurement of fragmentation and provided the ability to determine volumes and possibly derive mass distributions of particle sizes directly. Anderson et al., (2007) successfully applied 3D imaging to the measurement of iron pellet sizes, which showed good similarity to the distribution determined by sieve analysis. Thurley (2009) used a 3D laser scanning system to measure fragmentation distribution from the 3D profile of rock in a load-haul-dump (LHD) bucket and material on a conveyor and subsequently in a limestone quarry (Thurley, 2011). Photogrammetry has also been applied in the measurement of rock fragment size distributions on conveyors and muck piles despite challenges arising from the methods of assessment. The future of fragmentation analysis is further emphasised by Raina (2013) who found that the future of DIAT would dwell on different technologies in either isolation or combination, to deliver real-time monitoring and reporting of fragmentation.

3.3.1 Camera technology

The use of video camera technology is an alternative to laser scanners for measuring fragmentation. This technology was used in High land valley copper mine (located in Canada) where they installed an image analysis system (WipFrag developed in Canada) to monitor feed size distribution of ore (Sikmus and Dance, 2009). The video camera was fixed at an appropriate location with a lighting system to provide good lighting conditions. A typical example in the case of the South African case study is when Anglogold Ashanti Kopanang gold mine and the Council for Scientific and Industrial Research (CSIR) Mintek division investigated various methods of measuring and monitoring rock fragmentation, as part of the Future Mine project in 2003-2004. A Nikon D200 camera system and Canadian WipFrag software were installed for the continuous real-time particle size distribution of material on a conveyer belt. According to Brink et al., (2008), the Nikkon digital camera captured images of the flowing rock in every two minutes and images were sent through a transmission control protocol (TCP) or internet protocol (IP) to WipFrag software on a surface where the image was processed and a fragmentation curve generated. Brink et al., (2008) further explained that the daily, weekly and monthly fragmentation profile was posted on the mine's website. The underground installation system over a conveyor belt on level 74 of Kopanang Mine is shown in Figure 3.3.

Figure 3.3 Nikkon digital camera and lighting system installed over a conveyer at level 74 Kopanang mine (Source: Brink *et a*l., 2008)

3.3.2 Unmanned aerial vehicle technology

UAV technology has been used in the mining environment for various purposes such as measurements, monitoring and volume calculations. A commercial UAV with an integrated camera[23] that has the ability to capture high-resolution images and videos was investigated in measuring rock fragmentation at the University of Toronto Institute of Aerospace Studies (UTIAS) indoor robotics laboratory (Bamford et al., 2016). Bamford et al., (2016) outlined key benefits of using UAV system for fragmentation analysis in terms of its ability to collect and analyse fragmentation data rapidly and in real-time; reduces cost and provides high-resolution data collection; the system also keeps the operator out of the danger in a real mining environment. Bamford et al., (2016) emphasised the need for further work on the use of UAV for fragmentation analysis to be conducted in a real mine environment to gain further knowledge in the ability for the system to be incorporated into mine-to-mill optimization, its value addition as well as accuracy prediction.

Sanchidrian et al., (2009), realised that the “image analysis method of fragmentation measurement, resulted in an error of not more than 30% of the coarse region of the rock size distribution and an error of 85-100% in the fine region of the same distribution. This implies that an image analysis technique is not reliable for fine particle size determination. Bamford et al.,(2016) are of the view that despite the limitations of using image analysis for fragmentation measurements, it is still the common method used to measure rock fragmentation in mines. Some of these

[23] Parrot Bebop 2 specification UAV with 14 megapixel camera resolution; Video resolution (1920x1080 pixels, 30 frames per second); Flight time of approximately 25 minutes; Operating range is up to 2 km; Battery type is lithium polymer 2700mAh; Flash storage 8GB, Weight is 500g; Networking Wi-Fi MIMO Dual Band 2.4 and 5GHz (https://www.parrot.com/fr/drones/parrot-bebop-2#in-the-box)

limitations in two-dimensional (2D) image analysis technique as described by Bamford et al.,(2016) when the camera is located at the base of the muck pile are:

- Technicians must place scaling objects on the rock surface;
- Photos to be taken at a distance of <8-20 m from the rock pile which; may expose technicians to risk or interrupt production;
- A limited dataset can be collected from a limited position;
- Image may be obstructed by dust, fog, particulates or snow;
- Image accuracy may be influenced by the shape of the muck pile; and
- Lighting conditions may affect the results of the image analysis.

3.4 Technology options for grade analysis

Ore telemetry, such as sensors and sensor-based technologies are proposed to be a very important piece in achieving a future digital mine. Sensors such as ore telemetry and sensor technologies for sorting provide valuable information throughout the mine value chain from exploration to the final stages of the ore preceding final comminution stage (Klein et al., 2011).

The issue of grade control has been critical and managed in many mines - often with the intention to maximise the grade of the ore delivered to the surface. Very often, the higher-grade ores and easily accessible ores are depleting, leaving a large proportion of the remaining deposits at deeper levels below the earth's surface. The cost of grade controlling from such depths is likely to be higher and therefore Klein et al., (2011), proposed the need for state-of-the-art technologies to mine complex and deeper deposits using smart technologies with minimal physical influence and at low cost.

Despite the improvement of evaluation techniques, with the introduction of various statistical methods and analysis, the issue of obtaining a representative sample remains a challenge. Furthermore, the process of acquiring sampling data still relies heavily on outdated sampling methods. Work done by the old (COMRO) in the late 1900's on the gold analyser and other works by (Hill and Garber, 1978; Davies, et al., 1979; Sims, , 1980; Magri and Hawkins., 1987) have not been pursued making the industry to revert to the use of conventional sampling techniques like core drilling and chip sampling. Considering the advancement of digital technologies, it is necessary to re-introduce technologies that meet 21st-century mining requirements such as the gold analyser which can scan deeper into surfaces (beyond 1m-5m) and possibly 30m beyond the rock face. Such technology is presently not existent and therefore serves as an opportunity for local manufacturing.

Hyperspectral imaging may also be applicable because of the spectrum acquired at each point of the image, which does not necessarily require prior knowledge of the sample[24]. An example is the ProSpecTIR hyperspectral sensor manufactured by Southern mapping.

3.4.1 Measurement and monitoring of metal content

Ore sorting is not a new concept and has been used in the mining industry for many years. The technology has advanced from the traditional hand sorting techniques to the first electronic sorting equipment first produced in the late 1940s (Wills, 1992). In the 1970s and '80s, radiometric sorters were used in Buffelsfontein gold mine to separate coarse gold and uranium-bearing rock from waste, since density separation technique

[24] http://www.southernmapping.com/aircraft-systems/.

could not work in the case where all the rock types have a similar specific gravity (Ketelhodt, 2009). Wotruba (2006) and Salter and Wyatt (1991) emphasised sorting as a promising separation and preconcentration technology for the minerals industry plus further opportunities. A wide range of sensors in accordance with their mineral applications and methods of analysis are outlined in Table 3.2. Sensor technologies have the capability to analyse surface and bulk properties.

Table 3.2 Sensor technologies and their applications

Method	Analysis	Application
Photometric	Surface	Coal, sulphide, phosphate oxides
Radiometric	Bulk	Uranium, gold
Conductivity	Bulk	Metal sulphides, native metals
X-ray Fluorescence	Surface	Metal sulphides, limestone, iron
X-ray Fluorescence	Surface	Diamond, sulphides, oxides
X-ray Transmission	Bulk	Coal sulphides
Electrostatic	Bulk	Salts, halite
Magnetic	Bulk	Iron, quartz, kimberlite

Source: Salter and Wyatt (1991)

The optical method of on-line measurements uses colour line scan cameras and illumination from light sources. Some limitations with the optical system are their inability to penetrate surfaces and required feed preparation to ensure the surfaces are clean. This limitation is overcome by electromagnetic sensing techniques which are able to penetrate surfaces. There are several X-ray technologies such as the thermo scientific portable analyzers and Innov-X, used in core logging and grade control for mineral characterization purposes. Conductivity sensors are metal detectors applicable for discerning native metal such as gold and copper and metal sulphide ores. The

University of British Columbia (UBC) and MineSense Technologies Ltd developed conductivity-based technologies for various sorting applications.

The gold analyser (Figure 3.4) is an innovation by the now-defunct COMRO. It was used to scan ore bodies for grade results. Lerm (1994) conducted testing during which he performed significant sampling to explain the phenomenon of apparent gold loss on a mine. He outlined the advantages and disadvantages of the gold analyser and emphasised the need for future technology development to an acceptable production form.

There are other portable hand-held X-ray fluorescents (XRF) analysers developed by various vendors over the years for the analysis of precious metals. One such vendor is Bruker's represented by IMP innovations in Southern Africa. The handheld grade analyser is able to determine within seconds the metal content in materials containing gold such as jewelry, pins, ore, coins and many more (Bruker's elemental cooperation, 2014). However, because gold is found in very low parts per million levels, no handheld XFR can accurately detect its content in ore underground since the limits of detection of these handheld XRF’s are high. This is an opportunity for further research to be undertaken in this area to extend the calibration of handheld XRF’s to enable their limits of detection to be lower and possible to work in an underground mine.

Figure 3.4 COMRO grade analyser (Source: COMRO, 1990)[25]

3.4.2 Enabling technologies for digital mining

An advanced ore body proposal would be ideal for the research, development, and testing of a novel sensor that is able to see through rock and is linked to a smart production system. Such a prototype is aimed at modeling grade distribution and other orebody parameters (such as density) beyond the mining rock face. This would be aimed at integrating ore body definition and evaluation ahead of the work face, with the mine plan (layout) and production system.

3.5 Technology options for measuring density

There are various methods of density measurements as discussed in the previous chapter. Table 3.3 is a list of handheld density meters designed by various original equipment manufacturers for measuring density in various media types such as liquid, gas and other custom density tests. The limits of temperature (between 0°- 80° C) and density are also outlined in Table 3.3. The density meter with the highest temperature

[25] This is the best quality image obtained though the assistance of Dr. Declan Vogt.

and density range is the digital hydrometer/Specific gravity (SG) tester — ultra max (0-80 °C and 0.0-3g/cm^3).

Table 3.3 Handheld technologies for measuring density in various media

Density measuring device/Instrument	Description and Application	Manufacturer	Temperature	Density Range	Media type
1. Handheld Density/Specific Gravity Meter - Density - Hydrometer	The instrument is used for measuring density and specific gravity	Canon Instrument company	41 - 95 F(5-35◦ C)	0, 0-2g/$cm^{3)}$	
2. Digital Hydrometer/Specific Gravity Tester SG - 1000/Density Instrument Hydrometer	Designed to measure the temperature compensated specific gravity of batteries. Critical to determining the charge level of lead-acid batteries, without touching any liquid.	Eagle Eye Power Solutions, LLC (Limited Liability Company).	41-104 F (5-40◦C)	1-1.3gcm^3	Liquid
3. Digital Hydrometer/Specific Gravity Tester SG - Ultra	Measures accurate temperature-compensated specific gravity, density related values. SG-Ultra is commonly used for battery testing (Lead-acid and Ni-cad), alcohol and food	Eagle Eye Power Solutions, LLC (Limited Liability Company).	32-104 F (0,0-40◦C)	0,0 – 2g/cm^3	Liquid, gas

	testing petroleum testing and other custom density tests.				
4. Digital Hydrometer/Specific Gravity Tester SG – Ultra.	Measures density and density related values of samples within seconds. Results appear on large Liquid Crystal Display (LCD) screens and ready to be stored. Industrial and field applications include battery testing or utility telecoms, food and beverage quality control, biotechnology and many more	Eagle Eye Power Solutions, LLC (Limited Liability Company).	32-176 F (0,0-80°C)	0-0.3g/cm^3 (0,0 – 187 IBS/ft^3)	Liquid
5. Spap 40 / digital alcohol meter	5. Tailored to the needs of small distilleries and home distilleries	Anton Paar	41-86 F(5-30 ◦C)	0% v/v to 100% v/v	Liquid

6. Portable Density meter - DMA 35 Ex	Certified for use in areas where there is a risk of explosion. For e.g. in the chemical industry and for concentration measurement of battery acid.	Anton Paar	0 - 40 ◦C	0-2 g/cm^3	Liquid

Source: Compiled from engineering 360 IEEE global space website (http://www.globalspec.com/)

A sensor tool such as density analyser for the measurement of density in solids would be appropriate for a digital mine. The data collected by the sensor system, laser scanners, and other digital technologies will result in the collection of big data, and therefore the concept and technique for analysis would be discussed in subsequent sections.

3.6 Big Data solutions

Laney (2001), defined the three dimensions of big data as having (velocity, volume, and variety), known as the three V's. Technology firms such as International Business Machine (IBM) defined big data as data arriving from systems, sensors and mobile devices or multiple sources at a startling rate of velocity, volume and variety (IBM website). Big data analysis requires optimal processing power, analytic capabilities and skills to extract meaningful value from the data for a particular business case. Simon (2014) in his book "Too Big to Ignore", admits there is no perfect definition for Big Data. Renowned technology firms such as Google, Facebook, Amazon, IBM, LinkedIn, Twitter, Apple, and many others make use of big data. Big data was used in many other sectors such as politics where politicians used big data to identify and drive voter turnout in swing states (Farr, 2012). Businesses like the UPS frequently extract trucks delivery data to enable an optimised routing path to decrease expense and a business case on Big data for Pizza by (Simon, 2014). Simon (2014) further argues that big data is not exactly the solution to a dying business or restore the incompetence by management or a panacea to a broken corporate culture. The biggest outcome of big data is the possibility of finding useful information that can be used for effective decisions.

3.6.1 Techniques used in big data

According to Mckinsey Global Institute (2011), various technologies and techniques are available to collect, manipulate, analyse and visualize big data. These techniques and technologies originate from subjects including computer science, mathematics, statistics, and applied economics. Big data techniques are listed in Table 3.4. From Table 3.4, it can be deduced that techniques such as Pattern recognition, Data mining, Machine learning, Spatial analysis, Statistics and Time Series analysis would be applicable to this research.

Table 3.4 Big data computing techniques and descriptions

	Technique	Description		Technique	Description
1	**A/B learning**	Technique is also known as split testing or bucket testing . A control group is matched against a variety of test groups to determine what changes might improve a given objective. Big data enables large numbers of tests to be executed and analyzed to detect differenes between control and treatment groups.	7	**Network analysis**	Technique is used to characterize relationships among discrete nodes in a graph or network. In social network analysis.
2	**Association rule learning**	Used for determining relationships and "association rules" among variables in large databases.	8	**Optimization**	Numerical techniques used to redesign complex systems and processes to improve their performance according to one or more objective measures (e.g. cost, speed or reliability). Applications include improving operational processes such as scheduling, routing and floor layout, making strategic decisions such as prodct range strategy, linked investment analysis, R&D protfolio strategy. An example of technique is genetic algorithm.
3	**Classification**	This technique is used to identify categories of new data points based on the a set of training data points that have already been categorized. Often described as the supervised learning due to existence of a training set.	9	**Pattern recognition**	Machine learning technique that assigns some output value(or label) to a given input value according a specific algotithm. Classification technique is an example.
4	**Cluster analysis**	A statistical technique for classifying objects that splits a diverse group into smaller groups of similar objects, whose characteristics of similarity are not known in advance.	10	**Regression**	Statistical technique used to determine how a value of a dependent variable changes when one or more independent variables is modified. Used for forecasting or prediction. Applications include forcasting sales volumes based on various market and economic variables or determining what measureable manufacturing parameters most influence customer satisfaction. Used in data mining.
5	**Crowdsourcing**	Technique used for collecting large amount of data through a networked media such as the Web.	11	**Sentiment analysis**	Application of natural language processing (NLP) and other analyltic techniques to identify and extract subjective information from source text material. Examples include companies applying sentiment analysis to anlyze social media (social networks, microblogs nad blogs) to determine how different customer segments and stakeholders are reacting to their products and actions.
6	**Data fusion and data integration**	A set of technique used to analyze data from multiple sources to create a deeper understanding of such data that are usually more efficient and accurate than if analyzed as a single source. Examples of such techniques are signal processing and natural language processing.	12	**Signal processing**	Technique from electrical engineering and applied mathematics developed to analyze discrete and continuous signals (representations of analog physical quantities) even if represented digitally such as radio signals, sounds and images. This category includes techniques from signal detection theory which quantifies the ability to discern between signal and noise.

13	**Data mining**	Techniques used to extract patterns from large datasets through a combination of statistics and machine learning with database management. Examples of such techniques unclude association rule learning, classification, cluster analysis, and regression	19	**Spatial analysis**	Statistical techniqes used to analyze the topological, geometric, geographic properties encoded in a data set. Data from spatial analysis come from geographic information systems (GIS) that capture data incuding location information.
14	**Ensemble learning**	Type of supervised learning technique. Uses multiple predictive models based on statistics and/machine learning to obtain a better predictive models.	20	**Statistics**	the science of collection, organizing and interpretation of data which includes the design of surveys and experiments.
15	**Genetic algorithms**	A technique used in optimization that is inspired by the process of natural evolution or "survival of the fittest". Potential solutions are encoded as "chromosones" that have the ability to either combine or mutate. Individual chromosones are selected for survival in a modeled "environment" that determines the fitness or performance of each individual in the population.	21	**Supervised learning**	The set of machine learning techniques that infer a function or relationship from a set of training data. Examples include classification and support vector machines.
16	**Machine learning**	A field in computer science initially referred as "artificial intelligence", concerned with the design and development of algorithms that allow computers to perform certain actions based on empirical data. A focus of machine learning research is to automatically learn to recognize complex patterns and make intelligent decisions based on data. Example of machine learning is Natural language processing.	22	**Simulation**	Technique used to model behaviour of complex systems, often used for forecasting, predicting and scenario planning. Monte Carlo simulations for example are a class of algorithms that rely on repeated random sampling (running thousands of simulations, each based on different assumptions). The relust is a histogram that gives a probability distribution of outcomes. One application is the likelihood of meeting financial targets given uncertainties about thte suctess of various initiatives.
17	**Natural language processing (NLP)**	A subspeciality of computer science (also with a history in atrificial intelligence) and linguistics that uses computer algorithms to analyze human (natural) language.	23	**Time series analysis**	statistical and signal processing technique fuse for analyzing sequences in data points, representing values at successive times, to extract meaning ful characteristics from the data. Time series forecasting is the use of a model to predict future values of a time series based on known past values of the same or other series.
18	**Neural networks**	Computational models inspired by the structure and workings of cells and connections within a bain. Neural networks are well suited for nonlinear patters for example pattern recognition and optimization.	24	**Unsupervised learning**	A set of machine learning techniques that find finds hidden structure in unlabeled data. Cluster analusis is an example of unsupervised learning

Source: McKinsey Global Institute, (2011) According to Simon (2014), the five commonly used techniques for analysing big data include:

- Statistical techniques and methods such as regression (gives a deep understanding of the relationships among dependent and independent variables in a dataset) or A/B testing (in which different or refined variations of contents are compared with a baseline control;
- Data visualization enables organisations and people better understand their data in an interactive and creative interface. A basic chart or graph drawn in excel based on simple data is a typical example of data visualization. Companies like Tableau software, visually and IBM's data analysis software are examples of data visualization software;
- Automation is not a new concept; however, the prevalence of technologies has taken automation to an entirely new level. Some components of automation include Machine learning and intelligence, sensors and nanotechnology[26], RFID and Near frequency communication (NFC)[27];
- Semantics has to do with unstructured and semi-structured data. Some of the tools here include natural language processing, text analytics, and sentiment analysis; and

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[26] Nanotechnology is defined as the way in which discoveries made at the nanoscale (1 to 100 nm) are put to work. (http://www.nano.gov/sites/default/files/pub_resource/nanotechnology_bigthingsfromatinyworld-print.pdf)

[27] Near field communication is a contactless communication between devices such as smartphones or tablets. NFC devices allows information to be sent to other NFC devices without the devices coming into contact with each other. (http://nearfieldcommunication.org/)

- Predictive analytics is a tool used for instance by Google that enables the prediction of the right combination of words when mistakes are made. For example, “lhgt” instead of “light”.

Although big data has some limitations, in terms of it not being able to instantly eliminate problems in an organisation, according to Simon (2014) it may assist organisations in the following way:

- A better understanding of the past (what happened or what did not happen and why);
- Better understanding of what is currently happening or not happening and why; and
- A better understanding of the future i.e. what might happen or not happen.

3.6.1 Big data case studies

Several organisations have employed big data for the enablement of operational efficiencies. Such organisations include National Aeronautics and Space Administration (NASA) contest, gamification, and open innovation program (NASA, 2016). Explory’s data grid (a US-based company which has unlocked the potential of big data by integrating clinical, financial and operational data to provide a good healthcare system (IBM Corporation, 2016) and Quantcast(a web measurement and targeting company in California which is focused on connecting advertisers with their potential customers around the world (Quantcast file system, 2016).

The concept of big data is gaining momentum in the mining business. An example of a mining case where big data may be employed in the mining business is the spatial comparison between production plan versus actual. Such an exercise may enable new insights or trends to be uncovered in existing data. An appropriate visualisation program (for e.g. GIS software) can be a useful platform to enable images of spatial comparisons between the actual and production plan to be conducted using the block model information. The concept of visualization is subsequently discussed.

3.6.1 Visualization

Visualization is the creation of images one-dimensional (1D), (2D and 3D) diagrams, points, animations to communicate information. Several visualization techniques and technologies have been developed through innovative research in the creation of diagrams and images to improve the results of the analysis of big data. According to the journal of Geoinformation (Ward, et al., 2011), Geo-visualization was defined as the use of concrete visual representations, to make spatial contexts and problems visible, so as to engage the most powerful human information processing abilities, those associated with vision. Ward *et al.,* (2015), defined interactive data visualization as "communication of information using graphical representations". Pictures are widely and generally used to convey information. From different forms of visualization definitions (Geo visualization, data visualization and Pictures), it can be said that visualizations generally provide an alternative to verbal and text information. Early visualizations began in the Chauvet Pont d'Arc Cave, also known as the Grotte Chauvet-Pont Ardeche, located in a limestone plateau of the Adeche river in Southern France (UNESCO world heritage centre, 2016). It dates far back in the Aurignacian[28] period (30000-32000BP). The cave contained several images of dangerous animals

[28] Aurignacian Period is an Upper Paleolithic stone tool tradition, known to have a connection with the Homo Sapiens and Neanderthals in parts of Africa and Europe.

including mammoth, bear, cave lion, rhino plus prehistoric fauna and various human footprint. Figure 3.5 illustrates an example of the cave painting.

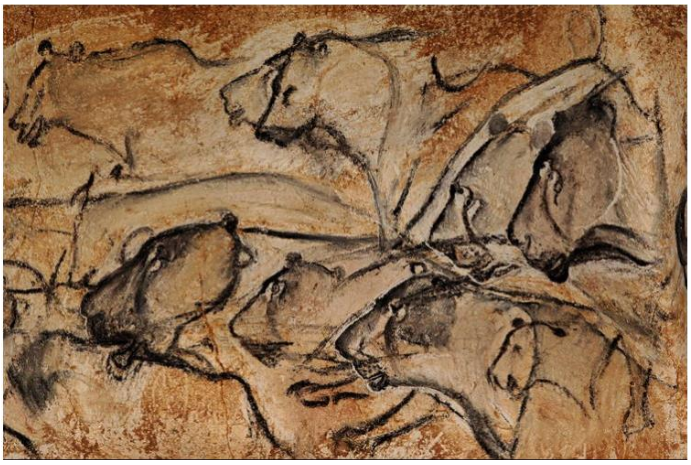


Figure 3.5 Decorated cave of Pont d'Arc (Source: Adapted from UNESCO World Heritage Centre, 2016)

Data in Microsoft Excel is able to create graphs and basic charts. Creative software such as the Tableau software also visually helps people and organizations to better understand their data no matter how big it may be.

For the purpose of this thesis, the ESRI GIS solution is an appropriate visualization tool for visualising the spatial comparison between the planned and actual mining data.

3.7 Relevant technologies discussed in this chapter

Figure 3.6 outlines some of the relevant technologies and big data analysis techniques that are applicable to this study and discussed in this chapter.

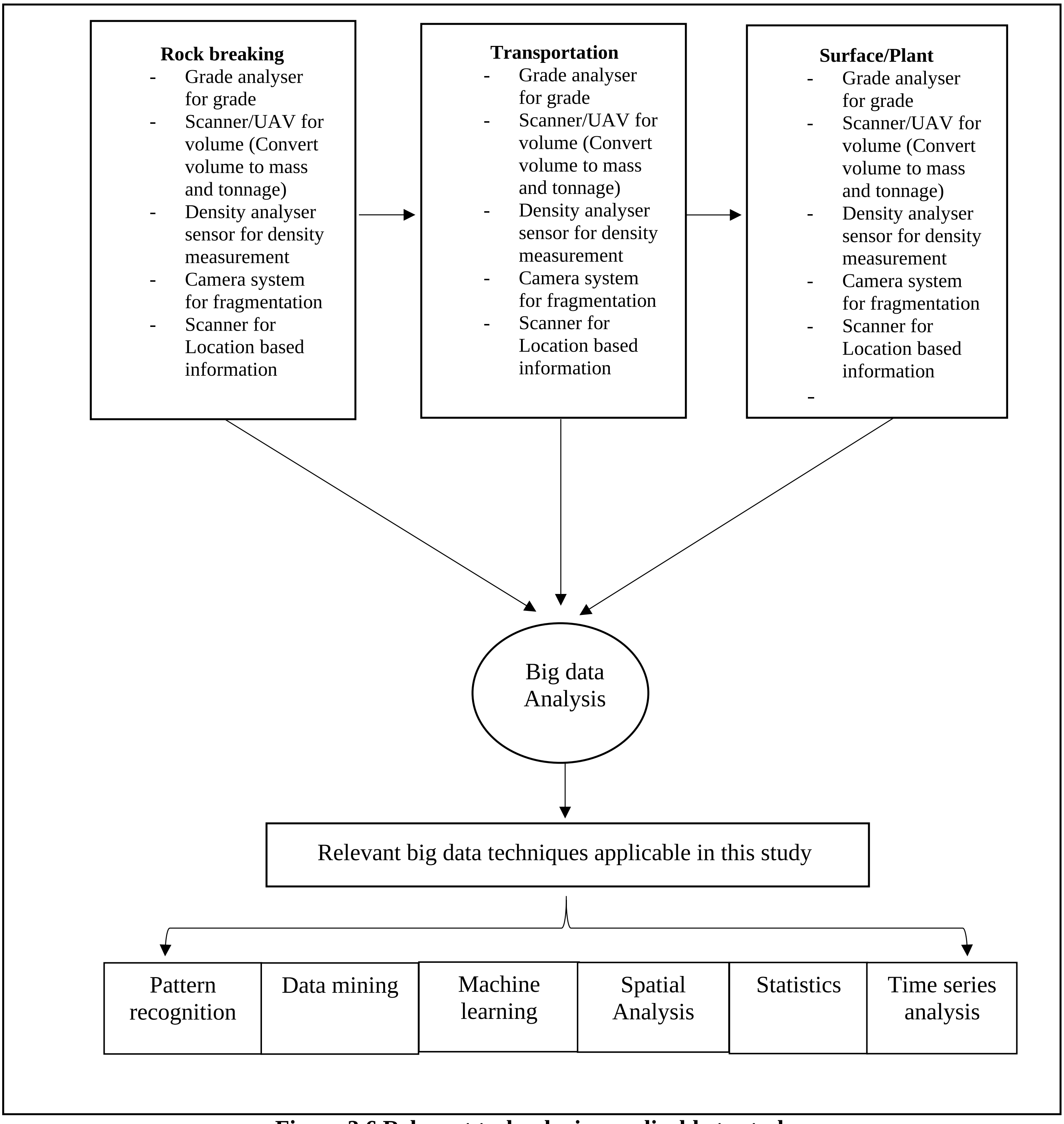


Figure 3.6 Relevant technologies applicable to study
(Source: Researcher's concept, 2019)

3.8 Conclusion

This chapter discussed various technologies that have been used in the past for tracking and measurement of broken ore variables. These include tracking technologies such as RFID for ore tracking; scanning technologies for measuring volumes; video camera and UAV for measuring and monitoring fragmentation; sensor-based technologies such as gold analysers for measuring metal content and; and the microdot technology to be tested in the thesis as a viable technology solution for ore tracking. Although handheld technologies are available for measuring density, the media type for use of these technologies does not include solids.

The concept of big data is discussed as data arriving from various systems, sensors, mobile devices and or multiple sources at startling volume, velocity, variety, and variability. Various statistical techniques are used to analyse big data which are often represented in various visualization software. The relevant data analysis techniques that would be relevant to this study includes Pattern recognition, Data mining, Machine learning, Spatial analysis, Statistics, and Time series analysis. Based on the existing technologies discussed in this chapter, the next chapter is focused on spreadsheet software options used overtime as well as leading practice software solutions for mine planning and reconciliation that have been used over time.

4 Leading mine planning and reconciliation software options

4.1 Introduction

Spreadsheet software, programs, and smart-device applications generally organize, catalogue and maintain data in a manner that is relatively easy to retrieve or recall, understand and interpret with charts and graphs hence creating an easiness to convert data into data analytics and dashboards. Various industries including oil and gas, mining, construction and government institutions (big or small) utilize spreadsheet and dashboards in one way or the other. This chapter discusses some software that have been used over time across various disciplines. Some mine planning and reconciliation software, recognized amongst industry-leading metal accounting practices, such as Snowden software, Deswik and MineRP are also discussed in this chapter.

4.2 General use of spreadsheets

Spreadsheets are still the most popular metal accounting tool and often complex to non-users. Spreadsheets are supported by specific file formats and compatible with specific operating systems. A list of some of the spreadsheet software and descriptions in terms of their data formats and compatibility with operations systems are outlined in Table 4.1.

Table 4.1 A list of spreadsheet software programs and their descriptions

	Spreadsheet	Description and functionalities	Advantage	Disadvantages
1	Microsoft Excel	An office mobile application with a familiar user interface that can be used in mobile devices. It can be used to review and edit documents. The software is available online and free to use. It runs on various operating systems such as Internet Explorer, Firefox, Chrome, Safari and Edge. The supported file formats include Microsoft Excel Open XML Format Spreadsheet File (XLSX), Excel Spreadsheet (XLS), Comma Separated Value (CSV), OpenDocument Spreadsheet (ODS).	It is popular, hence more of an industry standard. Easily accessible online and runs on various operating systems	Data can be manipulated. Data can easily be typed over and hence lose the originality or the records. Susceptibility to human errors.
2	Google sheets	Google sheets is a free online web application introduced in March 2006. It has all the capabilities of traditional online spreadsheet programs such as Microsoft Excel. Google Sheets can handle everything from simple task lists as well as data analysis with charts, filters and pivot tables. It runs on various operating systems including Android, Windows, Macintosh (Mac) operating system (OS), and Chrome OS. Some supported file formats are text (TXT), Tab Separated Values (TSV), Tablature (TAB), Microsoft Excel Open XML Format Spreadsheet File (XLSX) and Excel Spreadsheet (XLS), OpenDocument Spreadsheet (ODS), and (comma-separated values (CSV), Excel Open XML Spreadsheet Template file (XLTS).	Also, free and available online. Handles tasks and performs data analysis with charts and graphs similar to Microsoft excel	Difficult to manage data security issues due to free access online. It is also vulnerable to fraud and susceptible to human errors.

3	Apple Numbers	Numbers applications were developed by Apple Incorporated (Inc.). As part of the work productivity suite, it was developed together with keynote and pages. The operating system is MacOS, and supports various file formats including CSV, SaLt State (SLS), Open Document Format (ODF), XLSX (for import only), and PDF (for export only).	Simple to use and compatible with excel	It can only be operated on a Mac.
4	Libre office	An open-source productivity suite developed for Windows, Macintosh, and GNU[29]/Linux. It was developed in 2010. The libre office suite comprises programs to do word processing, slideshows, spreadsheets, diagrams and drawings, database maintenance and composition of mathematical formulae. It uses ISO/IEC standard documents file format to secure documents for all applications. Operating systems include Linux, Microsoft Windows, Free Berkeley Software Distribution (BSD) and OS X. Supported file formats include XLS, Hypertext Markup Language (HTML), XLSX (for import only) and Portable document format (PDF) for export only.	Libre office has good support in terms of a user manual	Libre office has fewer features when compared with MS excel.
5	Quattro Pro	This is a simple spreadsheet program developed by Borland and sold by Corel. The last stable release was in 2016. Supported file formats include HTML, XLS, XLSX (import only), PDF (export only).	Has a comparative advantage over excel with regards to the maximum number of rows and columns limits (1 million rows and 18276 columns)	Not user-friendly and also not common.

[29] GNU is a recursive acronym. It was developed by the GNU project which began in 1983 by Richard Stallman with the objective of producing non-proprietary software (https://www.techopedia.com/definition/3522/gnu)

6	Lotus 1-2-3	A command line spreadsheet program introduced in the '80s. It was designed by Mitchell Kepor and released in Jan 1986 by lotus software which is now part of IBM. The popularity of Microsoft excel exceeded the graphical user interface version of the spreadsheet. Lotus 1-2-3 was succeeded by lotus symphony.	Lotus 1-2-3 was fast. It could perform most of the tasks that excel did.	Although fast, it ran on DOS. Excel on windows was easier.
7	Apache open office Calc.	An open-source software that continually gets updated for security improvements and performance. It has all the industry standards of spreadsheets features and compatible with most operating systems.	The open-source software is free to download and free to use. Easy for beginners to use and advanced to perform experienced tasks that users may want.	The document format supported by the software is ODF and the commonest format in use is DOC format. Open software developers might be driven by their own interests instead of the needs of the end-user. It also gives the potential for malicious bugs and security risks to be introduced into the code.
8	Zoho sheet	Zoho sheet provides spreadsheet applications that enable you to organize data, discuss reports with teams and analyse data. It is also suitable for mobile devices as it provides apps for Android and iOS and therefore it does not chain users to their laptops.	Zoho sheets enable you to collaborate easily with colleagues online, hence improving the efficiency of the job done.	It requires the internet to use as it is web-based.

Source: Adapted from (Ranker, 2019; G2 CROWD, 2019)

4.2.1 Use of spreadsheets for metal accounting

Prior to the use of spreadsheets, traditional hand calculations were done. Spreadsheets were the first attempt of automating hand calculations. Today, the use of spreadsheets is a common practice across various technical disciplines in mining and metallurgy. A common challenge in using spreadsheets is that they do not allow for controlled data entry and they can easily be manipulated and corrupted. Another disadvantage in using a spreadsheet is their ability to type over data and lose the originality of records. There is also a possibility of data duplication or wrong entry of data in a spreadsheet, which is very difficult to detect later.

According to the AMIRA P754 (2007), spreadsheets are vulnerable to errors and also possess unjustified computations because the formulae in spreadsheets lack clarity and not always explained and recorded with the spreadsheet. The integrity of using a spreadsheet in a metal accounting system should also not be encouraged because it can easily be modified by metal accounting personnel to suit specific reporting needs. A better choice would be to use available commercial metal accounting software package. Hence the use of spreadsheets for metal accounting must be avoided. Basic examples of errors which occur when entering data into a spreadsheet or acquiring data from a spreadsheet include:

- Copying errors;
- Routing errors;
- Transposition errors;
- Errors due to inconsistency; and

- Errors in range (when a value is outside the range of a variable) (AMIRA P754, 2007).

The following steps are recommended in order to avoid input errors discussed previously:

- Do a manual check of data input;
- Consistency check of data and range;
- Validate data that is manually input;
- Analyse data for outliers (AMIRA P754A, 2007).

According to the AMIRA P754A (2007) code of practice, where home-grown spreadsheets are used, there should be clear rules for setting up such spreadsheets and these rules should state that:

- Spreadsheets must be in a single file;
- There should be no multiple linked files allowed; and
- There should be no macros or any other sub-form of programming written into the single file.

The reason for this is to ensure that the spreadsheet used is less complicated and can be maintained in the absence of the original designer. The AMIRA code further requires the rules to clearly state that the system should receive original input, which is to be verified by an independent party (AMIRA P754A, 2007). The rules must also state that the system must not receive inputs through links to any other file or system, except the data logging system. The reason, however, is to ensure that the accounting system remains truthful and not corrupted by wrong formulae and entries. The code also stipulates that no accounting data should be changed unless it has been explained with reason in a written report. It also requires approval from the appropriate level of authority which should be defined in the operation and the records of this retained for future reference.

Process engineers also use spreadsheets to solve problems of mass balance. Although the use of spreadsheets is not ideal, special computer programs are available to solve these complex problems (Roman, 1992). There are various classes of mass balance problems, however, what is common to all the classes is the conservation of mass which is a calculation that can be done on spreadsheets. Some classes of mass balance problems according to Roman (1992) are:

- Mass balance required when a process is being developed for a plant expansion;
- Mass balance required for the construction of a new plant; and
- Mass balance required when there are several process streams (including recycle streams) with many other components.

The various classes of mass balance requirements can be solved in a spreadsheet; however, this should be done in a systematic approach described in (Roman, 1992).

The use of spreadsheet software also for process simulation of dynamic stochastic systems in mineral processing plants was extensively discussed by Merks (2000). Various spreadsheet programs (popular ones are Excel, Lotus, and Quattro Pro) have been used for solving mineral industry problems and extensively discussed by (Meloy and Williams, 1992a; Meloy et al, 1992; Meloy and Williams 1992b; Meloy and Williams 1993; Meloy et al, 1993; Williams et al, 1991; William et al, 1993; William et al, 1995; Merks, 2000).

4.2.2 Spreadsheets used for mining production

The reporting of accurate data is important for effective mine production management control. This, however, may be a challenge for production supervisors to understand the importance of reporting such accurate data because of a drive to meet production targets and budget requirements. A simple spreadsheet known as the lotus "1-2-3" was developed by Lotus Software (which later became part of IBM) for the purpose of tracking production data. It was first released in January 1983. Although it was not the first spreadsheet application, it became the industry standard throughout the 1980s and the 1990s (Phillips, 1987). The format of the design of the spreadsheet is based on a problem solving and decision-making approach, usually to suit a particular operation. The format of the spreadsheet is in categories such as:

- Labour and benefit;
- Data on production;
- Detailed breakdown;
- Operating cost; and
- Capital recovery and other fixed costs (Philips, 1987).

The categories are related and therefore a change in one item automatically affects the others. Spreadsheets generally have additional functionalities that can be used for modeling financial and engineering problems. They also have the ability to unlock significant trends and patterns in large datasets. Some of the examples of the use of spreadsheets in solving engineering problems include:

- Performing matrix operations;
- Fitting curves and lines through data;
- Solving optimization problems;

- Evaluating integrals;
- Carrying out economic analysis; and
- Performing interpolation between data points (Mushaka, 2000).

Although there are various spreadsheets software available online as outlined in table 4.1, some of the criteria to consider when choosing a spreadsheet software for a project would be the purpose of the project, its availability, security issues associated with the use of that software. The next section highlights some mine planning and reconciliation software package in the mining industry amongst leading practice solutions.

4.3 Snowden software

Snowden Company does consult in the fields of geology (resource estimation), mining (mine planning related problems) and providing technical support to mining-related businesses at the corporate level (Snowden, nd). The company has developed various technical software for various purposes. This software and the tasks that they perform are outlined in Table 4.2.

Table 4.2 Snowden Software

Software	Task
Supervisor	Built to solve practical geological issues.
Reconcilor	An intelligence solution that enhances mineral recovery, improves plant efficiency, cost reduction, and productivity increase.
Regulator	It is a tool that enables the head office to take control of reporting governance information flow.

Bespoke development	Off the shelf solution to specific needs.

Source: Adapted from (Snowden, nd)

For the purpose of this thesis, a case study on the implementation of the Snowden reconciliation system at Telfer mine would be discussed.

4.3.1 Implementation of a new reconciliation system at Telfer mine

The Telfer project was first approved in November 2002 and reopened in June 2003. The project began to implement the Snowden's reconcilor software (Riske, et al., 2007). According to Riske et al., (2007), the reconcilor system is web-based utilizing the SZL server[30] with database importers. The system also utilizes reporting tools to obtain processes. It further presents mining information back to the users for analysis. Prior to the implementation, a detailed scoping study was done at Telfer which involved working with the site personnel to achieve the following:

- Definition of data and terms;
- Import/export requirements with formats; and
- Design the optimised reconciliation process flow and reporting requirements (Architecture) (Riske et al., 2007).

A schematic diagram of Telfer's reconciliation architecture is shown in the Figure 4.1.

[30] The SZL server is an application installed on HPC, data server and remote file store (including cloud resources). The data transfer is secure and fast. The server leverages SZL technology and transfers only data that is required to generate a specific plot (https://www.tecplot.com/products/szl-server/)

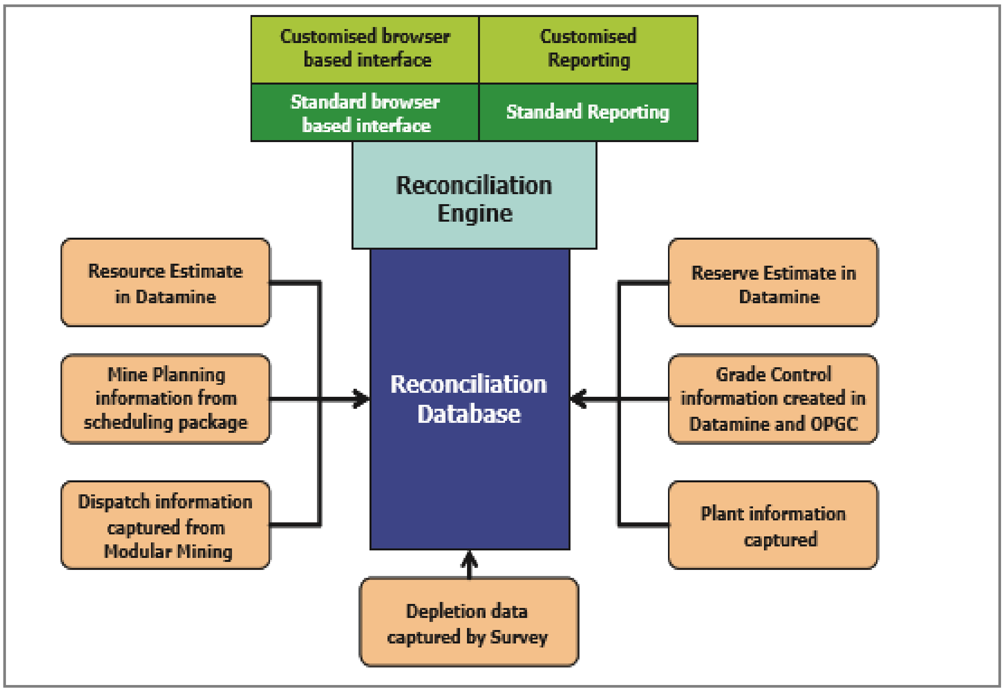


Figure 4.1 Architecture of the reconciliation system implemented at Telfer mine (Source: Morley 2003)

According to Riske et al., (2007), the reconcilor software was chosen due to its functionality, ease of use and cost-effectiveness. The system allows read-only access to users (unless administrative privileges including editing are given to users). Another advantage of the system is that because it is web-based, it does not require much training.

The reconcilor software provided Telfer with the required tools to capture, validate data from all the relevant sources so that a single set of numbers for mine tracking was secured (Riske et al., 2007). This allowed the staff to be proactive in analysing the data that was collected and taking proactive decisions with regards to defining accurate ore and waste on a day to day basis (Riske et al., 2007). Examples of reports generated by the reconciliation system at the Telfer mine include:

- Reports on material movement;
- Crushing by source;
- Model and material destination reports;
- Reconciliation reports;
- Daily block movement summaries; and
- Stockpile tonnes and grade balances (Riske et al., 2007).

The reconcilor system allows material to be closely tracked and delivered to the plant and provides information on the blended characteristics of the material being delivered to the plant. This information appears online on a shift basis and allows the plant personnel to understand how the different feeds to the plant would impact on the plant's performance (Riske et al., 2007). The reconcilor system further enables the comparison of truck weights, weightometer readings, and grade control estimates via pre-configured reports. Variances can be tracked by users to analyse trends and patterns or to identify equipment with calibration issues. By assessing variances, areas that require improvements in terms of their methodologies can be investigated. A screenshot of the Snowden reconcilor software designed on Telfer mine that provides the overview of material flow for a 24-hour period is shown in Figure 4.2.

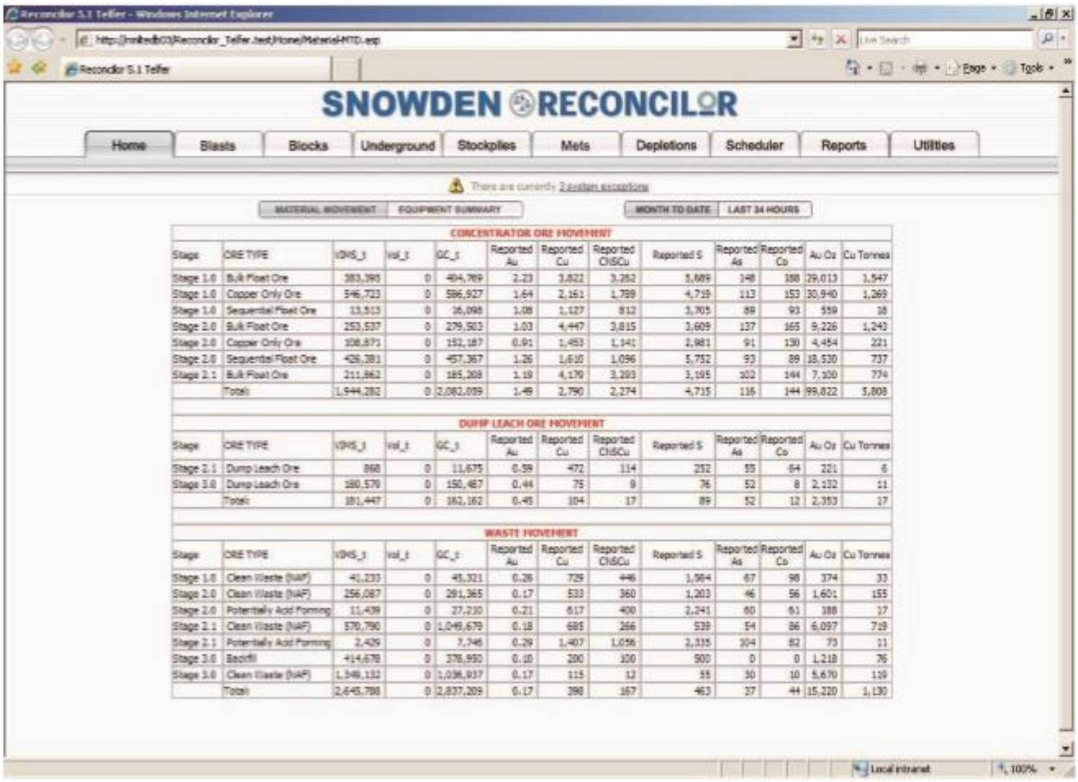


Figure 4.2 Telfer's reconciliation system for material tracking (Source: Riske *et al.*, 2007)

4.4 Deswik Software

Deswik Software was developed to enable high-performance technologies and provide software solutions that meet the demands of modern mining. Several software have been developed for mine planning, geology and survey. Some of these technologies/tools are depicted in Table 4.3 and discussed in the subsequent sections.

Table 4.3 Deswik Software Suite

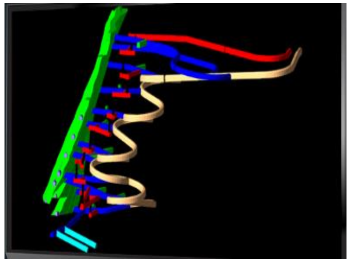
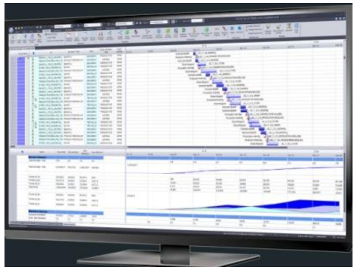
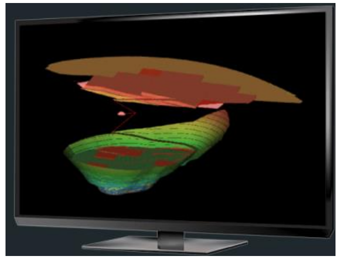
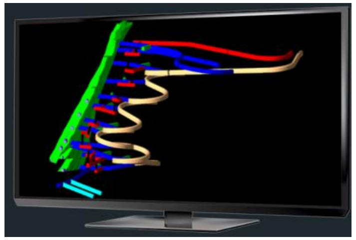
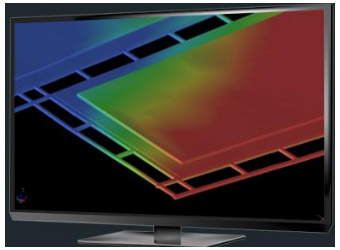
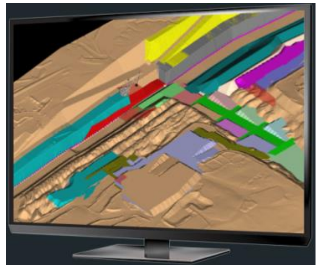
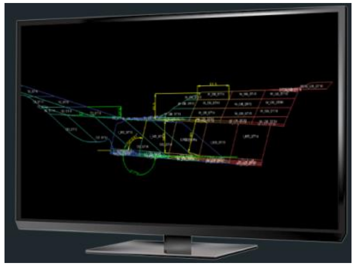
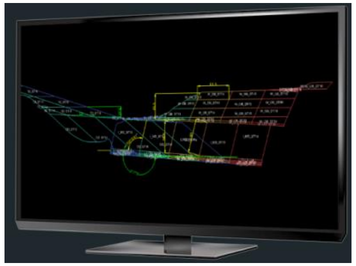
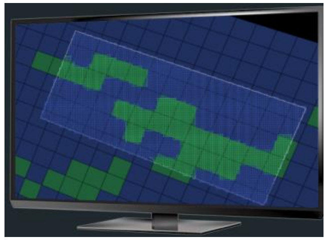
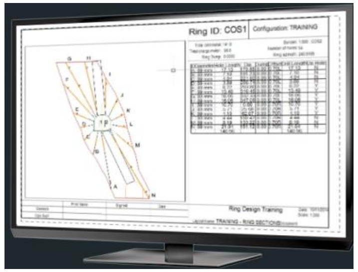
 Figure 4.3 Deswik. Computer-Aided Design (CAD) software	 Figure 4.4 Deswik Gantt chart scheduler	 Figure 4.5 Deswik Interactive Scheduler (IS)	 Figure 4.6 Deswik. (Landform and Haulage System (LHS)
 Figure 4.7 Deswik advanced underground metal system (AdvUGM)	 Figure 4.8 Deswik advanced open pit metals system (AdvOPM)	 Figure 4.9 Advanced Underground coal system (AdvUGC)	 Figure 4.10 Visual display Deswik. (Advanced Open Cut Coal) AdvOCC

 Figure 4.11 Visual display of Deswik. Aggregation (Agg)	 Figure 4.12 Visual display of Deswik. Auto Slope Design (ASD)	 Figure 4.13 Deswik.Caving software visual display	 Figure 4.14 Visual display of Deswik Dragline and Dozer Section Designer (DD)
 Figure 4.15 Display of Deswik. Draft software	 Figure 4.16 Visual display of Deswik Dig Optimizer	 Figure 4.17 Deswik Open Pit Drill and Blast Software	 Figure 4.18 Deswik Underground Drill and Blast (UGDB) Software

Source: Deswik (2019)

4.4.1 Deswik.CAD

The Deswik.CAD contains designs for solid modeling depicted in Figure 4.3. According to the Deswik website, key features of Deswik. CAD software includes:

- Fully featured CAD engine;
- Comprehensive mining design tools;
- Powerful Reporting;
- Survey Functionality;
- Integrated Data management;
- Auditability and consistency; and
- Inclusive format.

4.4.2 Deswik.Sched

This contains a powerful Gantt chart scheduler (Figure 4.4) designed to handle challenges of mine planning.

4.4.3 Deswik.IS

Deswik Interactive Scheduler is designed to bridge the gap between designing and scheduling. A screenshot of the Deswik.IS system is displayed in Figure 4.5.

4.4.4 Deswik.LHS

The landform and haulage system have been developed for scenario-based modeling and analysis. A screenshot of the landform and haulage system is displayed in Figure 4.6.

4.4.5 Deswik.AdvuGM

The Deswik Advanced Underground Metals software is developed specifically for underground metals operations. A screenshot of the Deswik Advanced underground metals is displayed in Figure 4.7.

4.4.6 Deswik.AdvOPM

The Deswik advanced open pit metals system is designed for specialized demands of open-pit metals operations. Figure 4.8 is a visual display of the Deswik advanced open-pit metal system.

4.4.7 Deswik.AdvUGC

The Deswik Advanced underground coal system as the name suggests is tailored towards the demands of the underground coal operations. A visual display of the Advanced Underground Coal system is shown in Figure 4.9.

4.4.8 Deswik.AdvOCC

The Deswik Advanced Open Cut Coal system has developed functionalities that are specifically tailored for specialized demands of open-cut coal operations. A visual display of the advanced open-cut coal system is displayed in Figure 4.10.

4.4.9 Deswik.Agg

The Coal Seam Aggregation software developed by Deswik is specifically designed for complex coal aggregation processes. This is to create a fit for purpose Run-of-mine reserves. A visual display of Deswik.Agg is displayed in Figure 4.11.

4.4.10 Deswik.ASD

The Deswik Auto stope designer is created to automatically design stopes for narrow vein vertical mining methods. A visual display of the Deswik.ASD Software is displayed in Figure 4.12.

4.4.11 Deswik.Caving

A Deswik software is purposely developed for modeling rock flow within the cave of Life-of-Mine to give recovery and dilution forecasts. Figure 4.13 is a visual display of the Deswik.Caving software.

4.4.12 Deswik.DD

A Deswik dragline and dozer section designer is a design tool with direct integration into Deswik's mine design, scheduling, and data management tools. Figure 4.14 shows a visual display of dragline and dozer software.

4.4.13 Deswik.Draft

The Deswik.Draft software is developed for drafting and plotting. A visual display is shown in Fig 4.15.

4.4.14 Deswik.DO

The Deswik digital optimizer is designed for designing open pit grade control dig lines. A visual display of the system is shown in Figure 4.16.

4.4.15 Deswik.OPDB

The Deswik Open Pit Drill and Blast software are developed for drill and blast design in surface mine methods. A visual display of the software is in Figure 4.17.

4.4.16 Deswik.UGDB

The Deswik underground Drill and Blast software is specifically designed for blast design in underground mining methods. The visual display of Deswik.UGDB software is shown in Figure 4.18.

4.5 Mine RP software solutions

MineRP is an enterprise resource planning solution for mining that connects the Science of Mining with the Business of Mining. Although it has developed solutions across various sectors including the oil and gas sector, construction and government, the focus for the purpose of this thesis are the solutions developed for mining in specific categories namely, managing mining data, understanding the mineral asset, determining the asset potential, and operating efficiently. According to the MineRP website, the solution brings together all the various technical data in a mine into a single platform. This allows the data to be analysed and viewed as a single picture. Further insights and trackable actions can, therefore, be done.

Mine RP defines a digital twin as a full representation of the physical assets and processes that are connected. Mine RP is able to create a 3D spatially intelligent digital copy of the state and status of the operation as well as its assets (MineRP, 2019). Each of these solutions is discussed in subsequent sections.

4.5.1 Managing mining data

The MineRP platform enables a full representation of all the technical mining data to be created on a single platform for viewing as a picture and further analysis. The system allows the creation of a 3D digital twin of the resource and mining operation and thereby enabling insights and trackable action to be made.

4.5.2 Understanding the ore body

In this solution, ore body knowledge is not limited to geology. The MineRP solution enables all aspects of the mineral assets to be represented in a single spatially indexed picture. Various analysis, planning, reconciliation and reporting of resources and reserves along the value chain is enabled. The digital capabilities under this solution are (MineRP, 2019):

1. Resource and reserve (R and R) governance: This system allows comprehensive management of resources and reserves during estimation and reporting. MineRP's solution has enabled the integration of geological, planning, and actual mining information enabling the mine to access real-time views of the R and R status; continuous insight into capital conversion rate/effectiveness; reduced risk of wrongly reporting; and predictive ore recoveries.
2. Transactional resource and reserve inventory: MineRP's GeoInventory patent enables the transactional management of Resource and Reserve (extending inventory management principles to mine production and planning control).
3. MineRP's volumetric spatial Information management system is an industry 4.0 solution which offers a platform where all spatial information is managed.
4. The spatially integrated digital twin is designed on a platform that brings all technical data created on a mine in a single platform where it can be viewed as a single picture.

4.5.3 Determine asset potential

The MineRP system enables the creation of strategic LoM plans that are fully integrated with Enterprise Resource Plan (ERP). This allows detailed business plans, budgets, and operation schedules to be done in the shortest time than it would take other mine planning software to do. The planning tools enabled by MineRP includes:

- Integrated mine planning: The spatial platform integrates all technical data onto a central Spatial dashboard (SpatialDB) and enables a rapid mine design and scheduling capabilities for all mining methods and commodities. The advantage with this system is that it enables multiple plans as well as budgets to be generated in days and not months as other mine planning tools would do.
- Unified Business planning: This solution enables the integration of Mine Planning and Business Planning for the purpose of financial recording of mine plans. This solution allows every mining activity (actual or planned) to be translated to its transaction in the ERP.
- Detailed short-term planning: This solution allows short term schedulers to consider the latest mining conditions, Human resources, maintenance demands, health and safety, as well as logistics and other constraints to create a mathematically optimised master business schedule to deliver on agreed production targets. One advantage of using MineRP's Planner's Enterprise Production Scheduler is that it allows and retains a spatial linkage to mine designs, geological and survey objects – which means all schedules can be visualised, animated and compared in a 3D space over a mobile platform or the web.

- Asset and resource management: The GeoInventory patent and Unified Mineral Inventory Management solution enables the optimal management of the mineral assets. This triggers best practices and processes in terms of production, logistics, and financial asset accounting.
- Spatially integrated digital twin: the spatially integrated digital twin brings together all the technical data created on the mine to be viewed as a single picture for further analysis.

4.5.4 Operating efficiently

The MineRP Platform delivers a single workspace for mine planning and execution to a detailed level and real-time control. The MineRP Platform allows:

- Detailed short-term planning;
- Orchestrated Dispatch and execution;
- Continuous data collection and tracking; and
- Real-time operations adjustment.

4.6 Comparative and gap analysis of current software solutions

From Table 4.4, it can be deduced that Mine RP software is able to bring together all the various technical data in a mine into a single platform enabling further analysis and viewing in a single picture. The digital twin representation of physical assets as well as the production status by the MineRP software gives it an advantage as the leading practice software solution for metal accounting. Deswik, on the other hand has developed several software suites for planning, geology and survey, but these have not been integrated. The Snowden software also has several functionalities (although less than Deswik) for ore and metal accounting but are not integrated into a single platform.

The outstanding functionality for all the software is the ability to do real-time ore tracking from underground to surface and in the metallurgical process.

Table 4.4 Comparative analysis of current software

	Required function for metal accounting	Deswik	MineRP	Snowden
1	Solutions for geological issues (enables aspects of the mineral assets to be represented).	✓	✓	✓
2	Solutions for mineral recovery, plant efficiency, cost reduction, and productivity increase.			✓
3	Tools for resource and reserve governance.	✓	✓	✓
4	Fully featured CAD engine (drafting and plotting)	✓	✓	
5	Mining design tools (for all mining methods)	✓	✓	
6	Reporting tools (for material movement, crushing by source, reconciliation reports, stockpile and grade balances, variance tracking).	✓	✓	✓
7	Survey Functionality	✓	✓	
8	Integrated data management system	✓	✓	
9	Gantt chart scheduler	✓	✓	
10	Data integration functionality		✓	
11	Read-only access to users			✓
12	Solution for creation of a 3D state and status of the operation	✓	✓	

Source: Researcher's concept (2019) based on sections (4.3, 4.4 and 4.5)

4.7 Conclusion

This chapter discussed some of the common digital tools for metal accounting that have been used over time. A list of spreadsheet software and their descriptions, file formats, compatibility with operating systems was outlined in Table 4.1. Although the commonest spreadsheet used in the mines is excel spreadsheet, others that have been used in the past for both mining production and metallurgical accounting are the lotus 1-2-3 and Quattro Pro. The AMIRA code of practice, however, does not encourage the use of excel spreadsheets for metal accounting because of the likelihood of having the spreadsheet system modified by a metal’s accounting personnel to suit specific reporting needs. To remedy such a situation, the code advises the use of an available commercial metal accounting software package. Rules pertaining to the use of spreadsheets for metal accounting is also discussed. Besides the use of spreadsheet by mining engineers to model financial and engineering problems, geotechnical engineers use spreadsheets to model and monitor the movement of side walls and rock supports. Snowden’s reconciliation software and its implementation at the Telfer mine in the North-Western Australia was also discussed. The Snowden’s reconcilor system is web-based and allows a read only access to users, however administrative privileges such as editing can be granted. This is an advantage of the use of spreadsheets in metal accounting where personnel may edit the spreadsheet to suit reporting needs. The reconcilor system provided the Telfer mine with the requisite tools to capture the accurate data, validate from all the relevant sources and therefore enabling a single set of numbers for ore tracking.

Deswik has also developed several software suites for planning, geology and survey. The software solutions although not integrated in a single dashboard, can be used in various mining methods and also for various metal commodities. The leading practice software solution discussed is MineRP software which has developed a spatial platform that integrates all mining technical data onto a central dashboard and therefore, the status of the mining activity can be viewed in 3D as a single picture. Other activities such as the mine design, scheduling, asset management can be done on this single dashboard. The outstanding functionality for Snowden, Deswik and Mine RP software is the ability to do real-time tracking of ore from underground to surface and in the metallurgical process (including the volume and in-process inventory measurements).

The outstanding functionality leads to the next chapter which investigates the suitability of the Microdots technology as a possible solution for real-time material tracking.

5 Real-time material tracking: Testing the suitability of the Microdots technology for ore tracking

5.1 Introduction

In the previous chapter, some leading mine planning and reconciliation software options including Snowden's reconcilor software, Deswik and MineRP were discussed. It was realised that the outstanding functionality for all three software is the ability to do real-time material tracking from underground to surface. This chapter outlines the procedures and results from testing the suitability of the Microdots technology (discussed in section 3.2.4 of chapter 3) as a viable technology for real-time material tracking. The chapter explains the reasons for conducting the test as well as the material safety data sheet from a South African and Canadian perspective. This chapter further outlines the procedure and results of the laboratory test work conducted using 10 000,5 000, and 3 000 Microdots aerosol systems. Observations after every stage of the test are made. Microdots from these aerosol systems were subjected to conditions including immersion in water, heating at 100°C, and crushing into coarse and fine samples. These conditions were used in order to simulate a typical mining environment. A strength, weakness, opportunity and test (SWOT) analysis of the Microdots technology in relation to RFID was also developed. In conclusion, a decision is made in terms of the Microdots technology's suitability for material tracking.

5.1.1 Rationale for conducting test

Microdots (not visible to the eye) are transparent polyester discs which are less than 1 mm in diameter (Veridot, 2016). The disc contains marked lines of text with a unique identification code (Veridot, 2016). The technology is used for various purposes including marking and tracking of vehicle parts using a unique numbering system. These unique numbers are only visible using a magnifying lens or an electronic microscope. The following may be possible if the Microdots technology is determined to be a viable ore tracking solution:

- **Material loss tracking**: If Microdots are found to be viable for ore tracking and it is possible to integrate the technology with the mine-to-mill optimization process, this can help in solving ore loss problems. Problems of material loss and incorrect routing arise when ore is being transported through ore transportation systems such as ore passes, skips, belts, ore trucks and locomotives. Ore reaching the surface is stockpiled at different locations or directly sent into the mill for processing. Discrepancies in terms of quantity and quality estimates usually arise when reconciling processed and stockpiled ores (actual) with the planned.
- **Better ore accounting and reconciliation**: According to JKMRC (2008), ore accounting involves the measurement and tracking of materials through the value chain from source to the production plant whereas reconciliation compares production estimates from the processing plant with estimates from the mine. An effective tracking system will, therefore, enable better accounting and reconciliation processes.
- **Ore blending and dilution**: when the unique Microdots identity is linked with the attributes of the ore, this will enable the processing department to better understand the ore properties of the material being delivered by the mine in real-time and ultimately improve blending and dilution activities.

5.2 Microdots technology and health and safety: Material Safety Data Sheet (MSDS)

The Canadian Centre for Occupational Health and Safety (CCOHS) defines MSDS as a document that contains information on the potential hazard (including health, fire, reactivity, and environment) of a chemical product as well as procedures adopted in working safely with such products (CCOHS, 2017). A distinctive feature about the MSDS of a product and its product label is that the former is prepared by the product manufacturer and contains more information about the product than its label. According to the CCOHS (2017), nine categories of information are required on an MSDS namely:

1. Product information: Product name, manufacturer and suppliers' names, and addresses as well as emergency phone numbers;
2. Hazardous ingredients;
3. Physical data;
4. Fire or explosion hazard data;
5. Reactivity data: information on the chemical instability of a product and the substances it may react with;
6. Toxicological properties: health effects;
7. Preventive measures;
8. First-aid measures; and
9. Preparation information in terms of who is responsible for the preparation and date of preparation of the MSDS.

The South African hazardous chemical substance regulations of 1995 under the Occupational Health and Safety Act, 1993, under section 9A discusses the handling of hazardous chemical substances. This section of the Act stipulates that every person involved in the manufacturing, import, selling or supply of any hazardous chemical substance for use at work, shall as far as reasonably practicable, provide the recipient of that substance without charge with an MSDS as per the guidelines of the International Standardization Organization (ISO) 1 1014 or ANSIZ400.1.1993. The information should include:

1. Product and company identification;
2. Composition of ingredients;
3. Hazard identification;
4. First-aid measures;
5. Handling and storage;
6. Exposure control/personal protection;
7. Physical and chemical properties;
8. Stability and reactivity;
9. Toxicological information;
10. Ecological information;
11. Disposal considerations;
12. Transport information;
13. Regulatory information; and
14. Other information.

After comparing the information on an MSDS required from a Canadian and South African perspective, the author perceives that although similar information is required, the South African regulation requires extra information. The next subsection reviews Microdots MSDS against the requirements of the South Africa hazardous chemical substance regulations of 1995.

5.2.1 Veridot MSDS

Holomatrix PTY Ltd developed the veridot MSDS. All relevant information required in the MSDS is described in Annex A4 based on the South African hazardous chemical substances' regulation, 1995 discussed in the previous section.

From Annex A4, it was deduced that Holomatrix MSDS provides additional information than the requirements of the South African hazardous chemical substance regulations, 1995, section 9A. The extra information pertains to fire-fighting measures and accidental release measures (discussed under numbers 15 and 16 of Annex A4). Although the statement under number 14 of Annex A4 (other information) advises that the information provided is based on the best available technical knowledge of the product, recipients of the product are however encouraged to fully understand and apply statutory requirements. It further instructs that recipients have the sole responsibility to take due precautions relative to the use of the product.

5.3 Microdots technology testing approach

The testing of the Microdots technology as a possible real-time ore tracking solution covers four stages (Refer to Figure 5.1). These include testing the distribution of the Microdots technology over an area and taking basic measurements of samples; immersion of samples into water for 24 hours; heating at 100°C (Microdot survives explosives to a maximum of 1200°C, but laboratory limitations allowed heating to a maximum of 100 °C); and crushing into coarse and fine samples. This approach was chosen to simulate mining conditions as practically as possible - bearing in mind laboratory limitations.

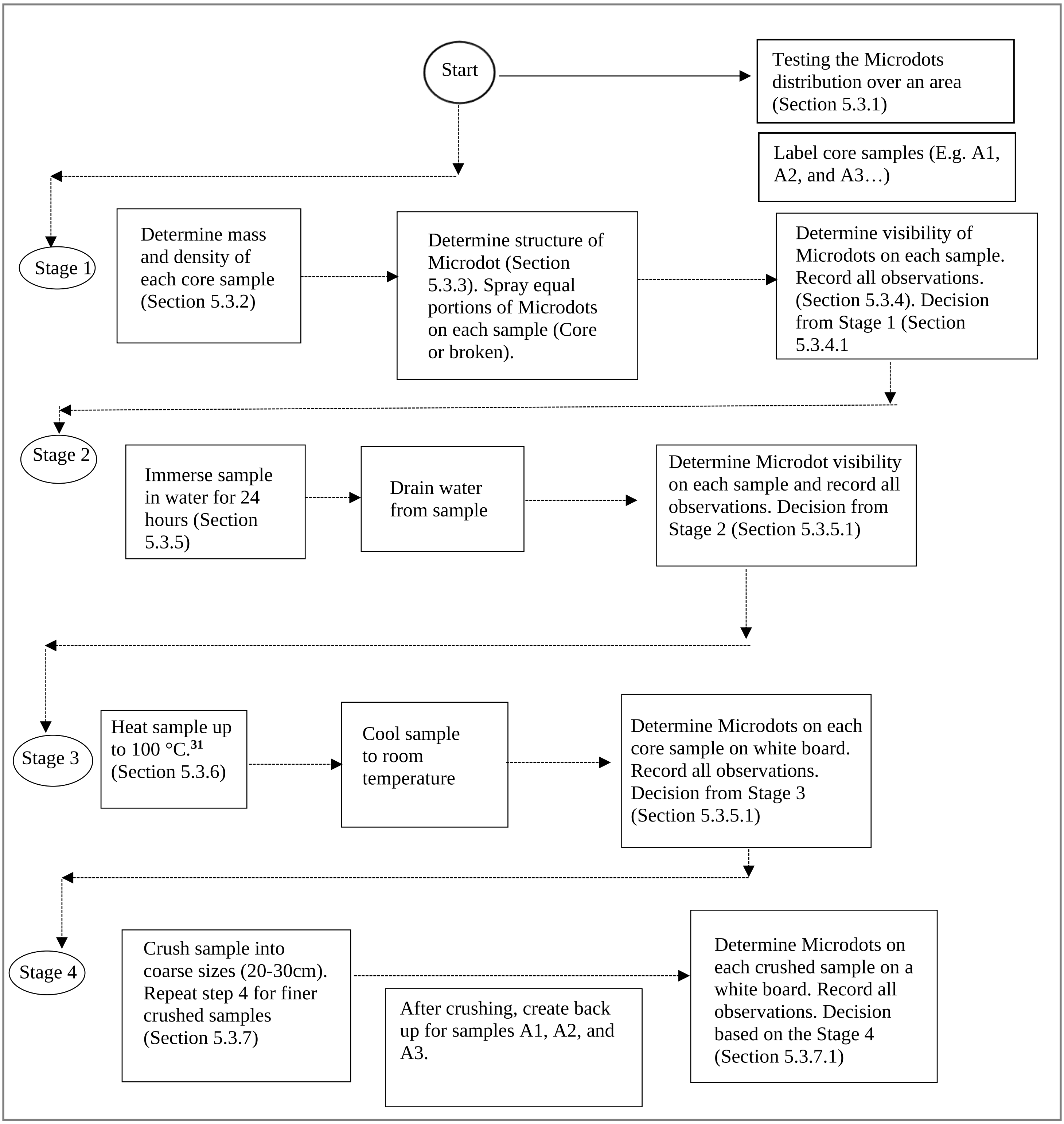


Figure 5.1 Microdot testing approach (Source: Researcher's concept, 2016)

[31] Although the Microdot technology can survive explosive temperatures up to a maximum of 1200°C, laboratory limitations allowed the test to be conducted to a maximum of 100 °C.

The Microdots aerosol systems [10 000 (A), 5 000 (B) and 3 000 (C)] are depicted in Figure 5.2 and observed after every stage of the test.

Figure 5.2 Microdots aerosol (10 000, 5 000 and 3 000) systems and their codes (Source: Researcher's concept, 2016)

5.3.1 Estimating the number of Microdots over an area

The purpose for this test is to estimate the number of Microdots that are likely be over a given area. To achieve this, Microdots were sprayed on a white piece of paper with dimensions 2.5cm x 2.5cm. The three aerosol systems (10 000, 5 000 and 3 000) were used in this exercise. Table 5.1 gives an estimation of the average number of Microdots within the 2.5cm^2 area and Table 5.2 estimates the number of Microdots on a sample area.

Table 5.1 Distribution of Microdots on 2.5cm x 2.5 cm area

Microdots distribution						
Square area = 2.5cmx2.5cm			Square area in square meter = 0.000625			
Paper	Box 1	Box 2	Box 3	Average		Average of 1 and 2
1	7	9	4	6.66667	7	6
2	5	4	4	4.33333	5	

Source: Researcher (2016)

Table 5.2 Estimate of Microdots around each sample

Area around specimen (m2)	Average number of Microdots	Square area in m^2	No of Microdots around sample
0.031531	6	0.000625	302.6967
0.031601	6	0.000625	303.3711
0.031531	6	0.000625	302.6967
0.031531	6	0.000625	302.6967
0.031531	6	0.000625	302.6967
0.031601	6	0.000625	303.3711
0.031531	6	0.000625	302.6967
0.031531	6	0.000625	302.6967
0.031531	6	0.000625	302.6967

Researcher (2016)

From Table 5.1, it can be estimated that the minimum number of Microdots to fall within the $2.5cm^2$ area are 6 Microdots. From Table 5.2, It was estimated that an average of 303 Microdots would be on the sample area. The next subsection highlights the basic measurements conducted on samples, the Microdot structure and its visibility on core samples.

5.3.2 Basic measurements of samples – Stage 1

Samples (9) were obtained from the anorthosite rock from the Bushveld igneous complex and was used for this test. Each sample was labelled as (Figure 5.3):

- Group one (1) consisting of specimen A1, B1, C1 coated with 10 000 Microdots;
- Group two (2) which is specimen A2, B2, C2, coated with 5 000 Microdots; and
- Group three (3) which is specimen A3, B3, C3 coated with 3 000 Microdots.

Figure 5.3 Anorthosite rock samples from the Bushveld igneous complex

(Source: Researcher, 2016)

Basic measurements (including mass, diameter, radius of sample, length of sample, volume and density) were conducted on each sample. The results of these measurements are recorded in Table 5.3.

Table 5.3 Basic measurements of samples

SAMPLE	MASS 1(g)	MASS 2(g)	MASS 3(g)	AVERAGE MASS (Kg)	DIAMETER (mm)	RADIUS (m)	LENGTH (m)	VOLUME (m^3)	DENSITY (Kg/m^3)
A1	985.800	985.900	986.100	0.986	47.400	0.0237	0.200	0.000353	2 795.061
A2	992.000	991.900	991.900	0.992	47.500	0.0238	0.200	0.000354	2 800.242
A3	985.700	985.600	985.600	0.986	47.400	0.0237	0.200	0.000353	2 794.210
B1	1000.400	1000.500	1000.600	1.001	47.400	0.0237	0.200	0.000353	2 836.356
B2	999.000	998.900	999.000	0.999	47.400	0.0237	0.200	0.000353	2 832.009
B3	993.700	993.800	993.400	0.994	47.500	0.0238	0.200	0.000354	2 805.041
C1	997.800	997.800	997.800	0.998	47.400	0.0237	0.200	0.000353	2 828.702
C2	994.600	994.600	994.600	0.995	47.400	0.0237	0.200	0.000353	2 819.630
C3	934.400	934.300	934.400	0.934	47.400	0.0237	0.200	0.000353	2 648.872

Source: Researcher (2016)

The average mass and density of all nine samples are depicted in Figure 5.4. Sample C3 recorded the least mass at 0.934 kg whereas sample B1 recorded the highest mass of 1.001kg. The average mass of all samples is 0.987kg. The average density of the samples is 2 795.569 kg/m^3. According to Roelofse (2010), the average density of anorthosite rock from the bushveld complex ranges from 2 370 kg/m^3 to 2 800 kg/m^3. The average density calculated for all nine samples falls within this range and hence the basic measurements are considered accurate and reliable, despite the fact that density varies with depth of rock.

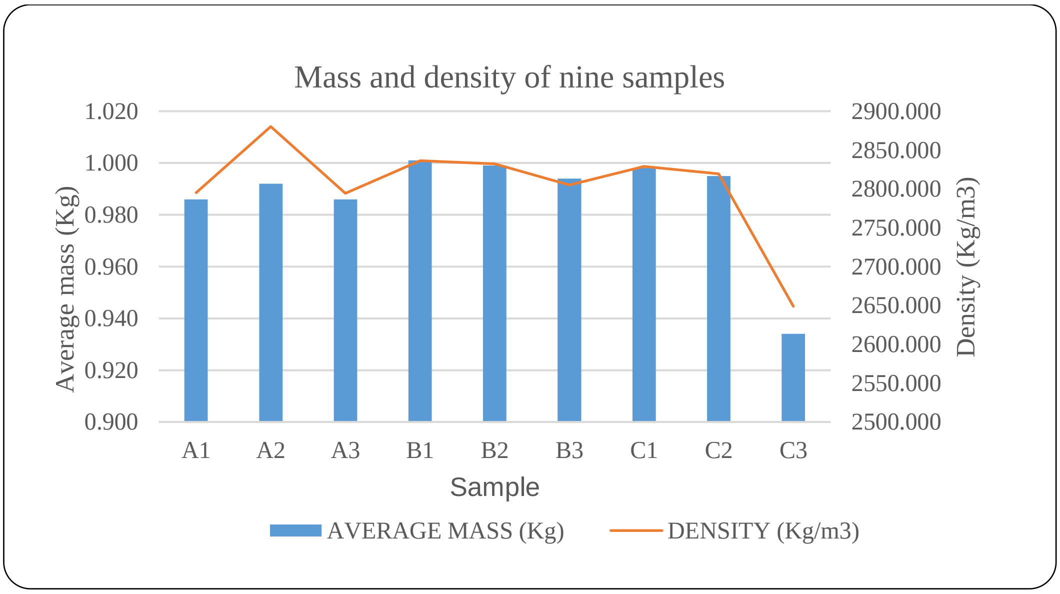


Figure 5.4 Average mass and density of nine samples

(Source: Researcher, 2016)

5.3.3 Determining the nature of Microdots – Stage 1

Before applying Microdots to samples, the structure of the text embedded to the Microdots were determined. Thin section cores were made at the Wits School of Geoscience and sprayed with 10 000, 5 000, and 3 000 Microdots aerosol systems. In order to determine the structure of Microdots, the sprayed Microdots were viewed under an electronic microscope (Olympus 93X4L). The laboratory was equipped with electronic microscopes and software (AnalysisGetIT) for capturing microscopic images.

Figure 5.5 Microdot shape and codes (Source: Researcher, 2016)

From Figure 5.5 (A and B), it can be seen that Microdots are hexagonal shaped discs with sizes ranging from 0.3mm to 1mm in diameter. A close observation of the codes in Figure 5.5 (A and B) and their respective barcodes (from the aerosol system pack) reveal that the Microdots are from 10 000 and 5 000 Microdots aerosol systems. Another observation made was that the codes were not etched onto the disc but rather are holes in the disc. The next subsection outlines the test for the visibility of Microdots on core samples.

5.3.4 Microdot visibility on core samples – Stage 1

In the previous sections (5.3.2 and 5.3.3), basic measurements and the text imbedded in the Microdots was determined. In this section, the visibility of Microdots on core samples (prior to immersion in water, heating and crushing) using 10 000, 5 000 and 3 000 Microdot aerosol systems was determined. The findings in this test is explained in Table 5.4.

Table 5.4 Microdots visibility on core samples

CORE SAMPLE	CODE	VISIBILITY	COMMENT ON MICRODOTS DISTRIBUTION
A1	10 000 Microdots= ZAVDTATHVX	Yes	Very Good - Microdots are distributed on the sample
B1		Yes	Very Good
C1		Yes	Poor - Few Microdots seen on the sample
A2	5 000 Microdots = ZAVDT97N7AN3	Yes	Very good
B2		Yes	Poor
C2		Yes	Good
A3	3 000 Microdots = ZAVDANVULC	Yes	Very good
B3		Yes	Very good
C3		Yes	Good

Source: Researcher (2016)

Decision after testing Microdots visibility on core samples

Results in Table 5.4 above showed that Microdots were generally visible by the naked eye although the unique codes could not be determined. Samples were viewed under the microscope (Carl Zeiss-Stemi 2000c) to determine codes. Microdots and codes were generally visible irrespective of the aerosol system that was used. The distribution of Microdots was classified as:

- Very good – meaning Microdots are evenly distributed around sample;

- Good - meaning Microdots are concentrated on one side of the sample; and
- Poor - meaning few Microdots are only present on the sample.

The next subsection outlines the results obtained from immersing samples in water for 24 hours.

5.3.5 Immersion of samples in water - Stage 2

Samples were immersed in water for 24 hours. The results are shown in Table 5.5.

Table 5.5 Results after immersing samples in water for 24 hours

SAMPLE	CODE	VISIBILITY	COMMENT
A1	ZAVDTATHVX (10 000)	Yes	Water has no influence on Microdots distribution on sample; the Microdots stick to sample; Microdots were visible under the microscope; codes were still readable
A2	ZAVDT97AN3 (5 000)	Yes	
A3	ZAVDANVULC (3 000)	Yes	
B1	ZAVDTATHVX	Yes	Water did not affect Microdots distribution; Microdots stick to the surface of the sample; Microdots are visible under microscope; codes are still readable.
B2	ZAVDT97AN3	Yes	
B3	ZAVDANVULC	Yes	

Source: Researcher (2016)

Decision after immersing samples in water

From observations in table 5.5, the researcher perceives that water has no influence on the visibility of Microdots since they were still visible on all the samples when observed under the microscope.

5.3.6 Heating of samples – Stage 3

Samples were placed in an oven and heated to a maximum of 100°C. The maximum blasting temperatures as discussed previously, ranges from ~ 1270 °C for tin and tungsten powders to ~ 2520 °C for aluminium, magnesium and titanium powders (Cashdoller and Zlochower, 1990). This implies that microdot would not be able to withstand explosives that generate heat exceeding 1200 °C. However, laboratory conditions enabled a maximum temperature of 100 °C in this test. Samples were then allowed to cool down to room temperature. The results of Microdots visibility after heating samples are depicted in Table 5.6.

Table5.6 Results of Microdots visibility after heating samples at 100 °C

SAMPLE	CODE	VISIBILITY	COMMENT
A1	ZAVDTATHVX	Yes	There was no influence of heat on Microdots. Microdots still stick to the surface of samples. Microdots were visible with the naked eye after heating and codes were visible using the microscope.
A2	ZAVDT97AN3	Yes	
A3	ZAVDANVULC	Yes	
B1	ZAVDTATHVX	Yes	The heat did not have any influence on Microdots; the Microdots still stick to the sample surface; Microdots were readable under the microscope.
B2	ZAVDT97AN3	Yes	
B3	ZAVDANVULC	Yes	

Source: Researcher (2016)

Decision based on water immersion and heating of samples

From results in Table 5.6, the researcher perceives that a maximum heat temperature of 100°C has no effect on Microdots visibility on core samples since the codes on all samples were readable under the microscope. The researcher therefore confirms at this stage that the data integrity of Microdots is not affected by water and heat (temperature at 100°C) irrespective of the aerosol system used (Refer to images in Figures 5.7, 5.8 and 5.9).

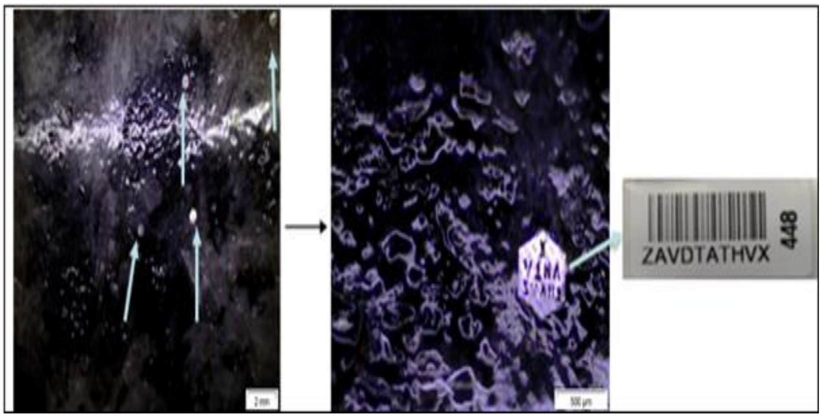


Figure 5.6 Microdots visibility after subjection to water and heat (Source: Researcher, 2016)

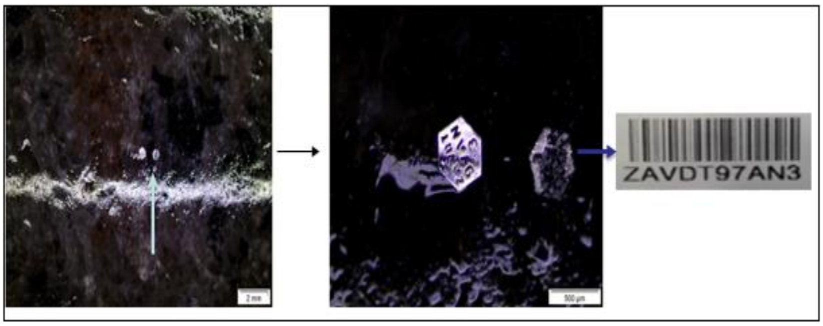


Figure 5.7 Microdots (5 000) visibility after subjection to water and heat (Source: Researcher, 2016)

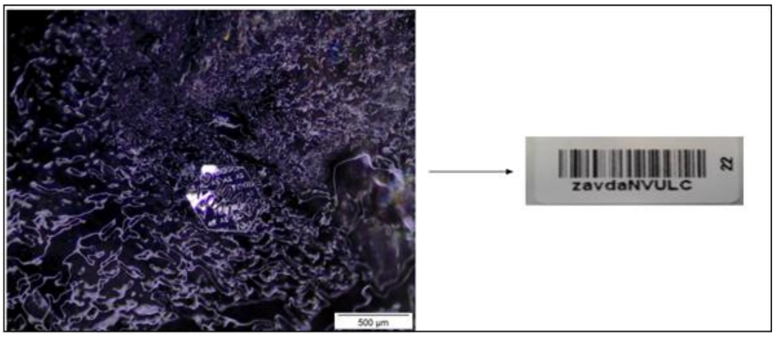


Figure 5.8 Microdots (3 000) visibility after subjection to water and heat (Source: Researcher, 2016)

5.3.7 Crushing samples into coarse and fine sizes – Stage 4

The fourth stage involved the crushing of samples into coarse and fine sizes. Crushing was done using the Rocklab crushing machine. The coarse sizes range from 2cm to 3cm, whereas the fine sizes ranges from 3.35mm to less than 1mm. After crushing samples into coarse sizes, Microdots were visible with the naked eye and the codes were readable under a microscope. Figure 5.10 depicts the visibility of Microdots on coarse crushed samples. The result of the visibility check conducted on samples is depicted in Table 5.7.

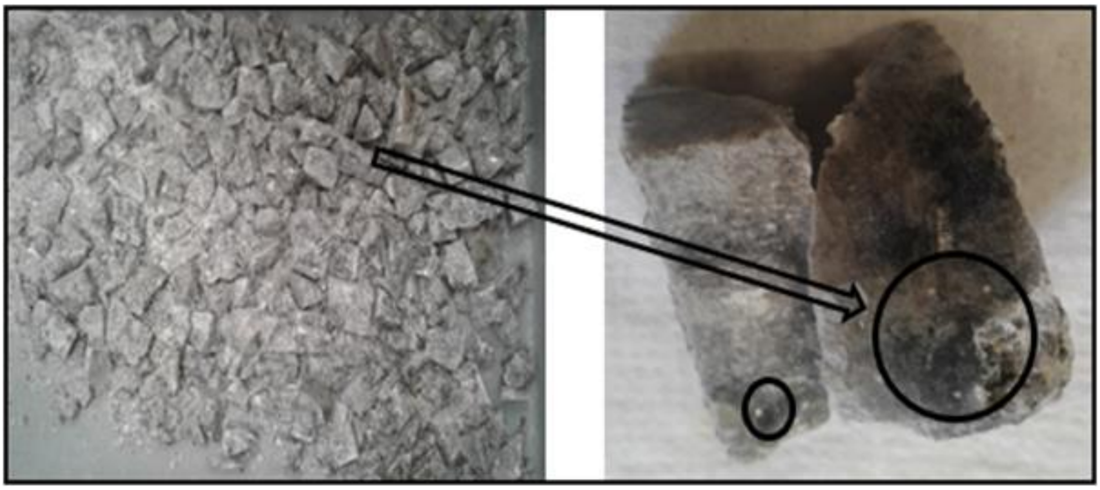


Figure 5.9 Microdots on coarse samples (Source: Researcher, 2016)

Table 5.7 Results of Microdot visibility check on coarse samples

<table>
<tr><th>SAMPLE</th><th>CODE</th><th>VISIBILITY</th><th>COMMENT</th></tr>
<tr><td>A1</td><td>ZAVDTATHVX</td><td>Yes</td><td rowspan="3">Microdots are still visible under the microscope; codes ate still readable; visibility was slightly impaired by dust; microdots still stick to samples.</td></tr>
<tr><td>A2</td><td>ZAVDT97AN3</td><td>Yes</td></tr>
<tr><td>A3</td><td>ZAVDANVULC</td><td>Yes</td></tr>
</table>

Source: Researcher (2016)

Results from Table 5.7 shows that crushing has no impact on the Microdot visibility. An interesting observation was the fact that dust generated from the crushing exercise had slightly impaired the visibility of Microdots, however, the codes were still readable.

Coarse particles were further crushed into smaller sizes (<1mm to >3.35mm[32]). Samples were further screened to classify them in sizes (>3.35mm, 2mm < size < 3.35mm, within 1mm and 2mm, and less than 1mm) as depicted in Figure 5.11.

32 Sizes were determined based on the available sieve sizes.

Figure 5.10 Screened samples into various fine sizes (Source: Researcher, 2016)

Visibility checks on Microdots were conducted on these sizes and the results are shown in Table 5.8.

Table 5.8 Visibility of Microdots in fine samples

Sample A1 sprayed with 10 000 Microdots					
Size distribution	Mass (g)			Visibility	Comments
3.35	67.600	67.600	67.600	Yes	Four Microdots were seen on four different broken particles; Codes on the Microdots couldn't be read due to dust cover.
2	195.500	196.900	197.000	Yes	3 Microdots were seen on samples and codes were readable
1	120.700	120.700	119.006	No	The particles are small and hence difficult to identify Microdots through a microscope
<1	150.006	150.009	151.003	No	
Sample sprayed with 5 000 Microdots					

3.35	86.000	85.600	85.700	Yes	Four Microdots were seen on four different particles. Codes on Microdots were readable under a microscope
2	205.300	205.000	205.300	Yes	Five Microdots were identified on four different particles. Codes were also readable under a microscope
1	109.700	110.500	110.500	No	Microdots could not be seen under microscope
<1	156.200	158.200	158.300	No	
Sample sprayed with 3 000 Microdots					
3.35	101.100	101.700	99.700	Yes	Three microdots were seen on three different particles. The codes were readable under the microscope
2	201.700	201.300	203.900	Yes	Two Microdots were seen on two different particles. Codes were also readable.
1	96.600	96.900	96.100	No	Due to the tiny nature of particles, it was difficult to see Microdots on any of the particles. No Microdot was visible under the microscope.
<1	132.900	133.300	133.600	No	

Source: Researcher (2016)

Results from all three aerosol systems indicate that the bigger the particle size, the higher the likelihood of finding Microdots on the sample. Results further show that Microdots are seen on particle sizes from 2mm upwards.

Figures 12 and 13 both depict Microdots visibility on particles of sizes greater than 2mm. A greater number of Microdots were identified on particle sizes ranging from 2mm to 3.35mm. Although codes were still readable under a microscope, the visibility of Microdots codes was impaired by dust generated during crushing. No Microdots were seen on particle sizes below 2mm. This is regardless of the type of aerosol system used (10 000, 5 000 or 3 000).

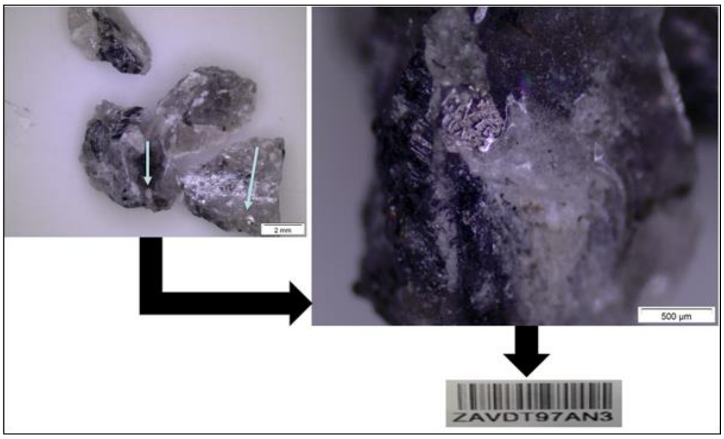


Figure 5.11 Microdots visibility on coarse sample A2 (Source: Researcher, 2016)

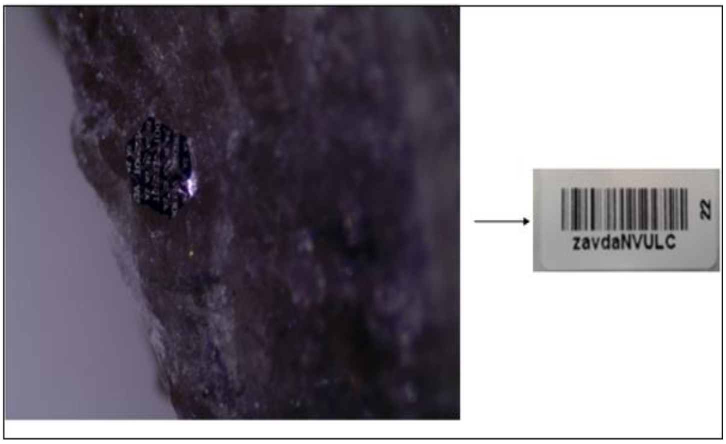


Figure 5.12 Microdot visibility on sample A3 (Source: Researcher, 2016)

Decision after crushing samples into coarse and fine sizes

In general, these results indicate that Microdots can be visible in both core and broken ore samples. However, the challenge with Microdots is its inability to be digitally tracked, detected and recorded. The technology's ability for use as a real-time technology for ore tracking is therefore questionable. The technology would therefore not be considered for use in the implementation plan chapter (Chapter 8). The next section develops a SWOT analysis of the Microdot technology in relation to RF tags.

5.4 SWOT analysis of Microdots in relation to RF tags

A SWOT analysis is carried out to identify the internal strength, weaknesses, opportunities, and threats of a project. These are classified as the four main elements or themes of that project. A SWOT analysis involves identifying the objectives of the project and outlining internal and external factors, which are either favourable or unfavourable to attain those objectives (Fallon, 2017). In this study, a SWOT study was undertaken to evaluate the Microdots technology as a viable tracking solution in relation to current tracking technologies in SA's mining industry.

Figure 5.14 is a SWOT diagram of the Microdots technology in relation to RF tags. Although there are a number of strengths identified (data integrity is retained after subjection to heat, water and crushing), the threats of the propellant of the aerosol system (being flammable) makes it a bad choice for example in the coal industry. This is because the coal industry is faced with frequent spontaneous combustion issues. The technology also may not be applicable in an underground mine because of limited ventilation issues.

Strengths	Weaknesses
• Data integrity of Microdot is retained after undergoing conditions such as water immersion, heating to 100°C and crushing. • Microdots stick to the surface of the core or broken rock. • The health and safety impacts of using the Microdot aerosol system can be minimised by the effective use of safety personal protective equipment (PPE). • Microdots unique code can be linked to ore attributes in a single database to enable the management of ore flow properties. .	• The Microdot aerosol system propellant is flammable. • The visibility of code is affected by dust. • Microdots do not transmit signals to a reader and hence detection of Microdot is done manually and not digitally.
Opportunities	**Threats**
Further opportunities to improve the technology includes: • How to enable real-time digital tracking of Microdots and their respective codes; • How to combine the technology in the ore flow process stream which is usually a complex one; • How to use the technology to ensure easy identification of mixed ore sources and their locations; • How to use the technology to prevent misrouting challenges; and • How to use technology to minimize risks and identify potential hazards in real-time.	• Due to the flammable nature of the propellant in the aerosol system, it cannot be used in the coal industry. • Due to the presence of dust in mine, it would be difficult to identify the codes of Microdots.

Figure 5.13 SWOT diagram of Microdot in relation to past and present tracking technologies (Source: Researcher, 2016)

5.5 Conclusion

This chapter highlights the laboratory test conducted in determining the potential of Microdots technology for real-time tracking using core and broken ore samples. As part of the requirement for health and safety, the MSDS based on the Canadian Centre for Occupational Health and Safety as well as the South African Hazardous Chemical Substance Regulations, 1995 was discussed. It was realised that the South African Hazardous Chemical Substance Regulations, 1995, has more requirements than the Canadian Center for Occupational Health and Safety. The MSDS developed by Holomatrix Pty Ltd is based on the South African Hazardous Chemical Substance Regulations, 1995.

The laboratory test involved the basic measurements conducted on core samples obtained from the Anorthosite rock samples of the Bushveld igneous complex. Basic measurements include the mass, volume, and density of all nine samples. The average density recorded is 2 795.569 kg/m^3 which falls within the density range defined by (Roelofse, 2010) of 2 730.000 kg/m^3 and 2 800.000 kgm^3.

The structure of Microdots was determined by cutting thin section cores, spraying the Microdots on these cores and viewing under the Carl Zeiss-Stemi 2000c electronic microscope. Laboratory test was carried out to determine the visibility of Microdots on core and broken samples using 10 000, 5 000 and 3 000 Microdot aerosol systems. Microdots were generally visible irrespective of the aerosol system that was used. Samples were immersed in water for 24 hours and the results showed that water has no influence on Microdots since the codes were still visible on all the samples when placed under the Carl Zeiss-Stemi 2000c microscope. Samples were placed in an oven and heated to a maximum of 100°C. Samples were then allowed to cool down to room temperature. Results obtained indicated that heat had no effect on Microdot visibility on core samples since codes on all samples were still readable under the microscope. After stages one (1), two (2) and three (3) of testing the suitability of the Microdots technology for ore tracking, the researcher confirmed that the data integrity of Microdots is not affected by water and heat. The final stage four (4) involved the crushing of samples into coarse and fine sizes. Crushing was done using Rocklab crushing machine. The coarse sizes range from 2cm to 3cm, and the fine sizes range from 3.35mm to 1mm. After crushing samples into coarse sizes, Microdots were visible with the naked eye and the codes were readable under a microscope. Coarse particles were then crushed into smaller ones (3.35mm-<1mm). Samples were further screened to classify them in sizes (>3.35mm, within 2mm and 3.35mm, within 1mm and 2mm, and less than 1mm). Microdots were seen on particle sizes from 2mm upwards.

A SWOT study was undertaken to evaluate the Microdot technology as a viable tracking solution in relation to RF tags which is currently being used in the mining industry. A positive strength identified in the Microdot technology, is its ability to retain data integrity after subjection to heat, water and crushing. However, the threat of the Microdot aerosol system makes it a bad choice in for example the coal industry which faces frequent spontaneous combustion issues. The technology also would not be suitable in an underground mine due to ventilation issues. Microdot technology would therefore not be considered as an option in the implementation strategy for the development of real-time material tracking, to be discussed in chapter 8.

The next chapter explores real-time material tracking with specific reference to volume and in-process inventory measurements. Attributes of mass measurements; metal accounting methods for in-process measurements, recovery and accountability, and mine to mill reconciliation concepts are explored.

6 Real-time material tracking: Volume and in-process inventory measurement towards real-time material tracking

6.1 Introduction

This chapter explores the concept of real-time material tracking with the focus on volume and in-process inventory measurements. As far as real-time material tracking is concerned, it is well understood that a considerable amount of metal is locked in various forms of metal inventory units across the value chain. These inventory units include both coarse and fine particles which are held in the process. Examples of coarse particle process hold-ups include metal locked in mine ore pass, ore bins, ore silos and run of mine stockpiles. The various units of stockpiles make it difficult to accurately determine the metal content in a unit of an in-process inventory. Several measurement errors are accrued over time which results in accuracy issues in the metal balancing and reconciliation process. Errors are also incurred due to density measurements used in converting volume into a dry mass. Thus, the chapter would highlight the theory of in-process metal inventory measurement methods. The tonnage is obtained based on the volume and the relative density of the ore determined using an appropriate method as discussed in (chapter 2) of this thesis. The chapter further highlights the truck mass measurement and surveyor's mass measurement. Here, accuracy issues for conducting volume measurements are also discussed. A typical mine to mill reconciliation process is also discussed. This serves as a build up towards the development of a conceptual framework for real-time material tracking.

6.2 Mass measurement

The objective of mass measurement for the purpose of metal accounting is to maximise accuracy and eliminate bias. According to Morrison (2008), mass measurement is considered to be credible when it meets the following criteria:

- The mass measurement is repeatable to within the defined criteria;
- In using different methods or equipment, the mass measurement is reproducible to within a defined error criterion; and
- The mass measurement is unbiased.

There are several methods for determining wet and dry mass. In selecting an appropriate mass measurement method, factors considered should include:

- The state of the material;
- The amounts processed; and
- The accuracy of the measurement required.

6.2.1 Accuracy of mass measurements

There are various factors that affect the accuracy of mass measurements and these include:

- The material being measured (particle size, size distribution, etc.);
- Equipment used;
- Calibration of equipment;
- Equipment maintenance;
- Operations conditions; and
- Measuring method (static, dynamic or hybrid) and protocols (JKMRC, 2008).

The less variability in particle size, the better the accuracy of the measurement. Generally, it is accepted that throughout the mining and metallurgical process, the accuracy of the mass measurement increases from the raw ore material until the final product is formed. This is because as the ore progresses through the mining and metallurgical processes, the components and sizes are more homogenous and the grades are much higher in smaller quantities (JKMRC, 2008).

There are several weighing equipment and methods of mass measurements that are applied throughout the mining and metallurgical processes. Some of these are discussed in the subsections below.

6.2.2 Truck mass measurement and surveyor's mass measurement

Truck mass measurement is usually compiled from a tally sheet compiled by a spotter[33]. A track tally system of loading and tipping can be developed and used to record the material movement from the mining face to various destinations. The surveyor's measured mass is determined based on the calculated volume. A truck mass is usually computed based on some factors. The truck mass and surveyor's mass is expected to be the same but usually not.

When comparing the truck mass and the surveyor's mass, a linear relationship is expected over a period of time. The correlation coefficient (R^1) in Figure 6.1 measures the intensity of the linear relationship existing between the two variables. The variable correlation coefficient is equal to 0.94 and hence indicates a strong linear relationship between the truck mass and the surveyor's mass.

[33] A person who manually records details of the truck whenever it tips the ore. Some of the details include grade of ore, name of truck driver, date of tipping, shift, destination of truck, and time of tipping.

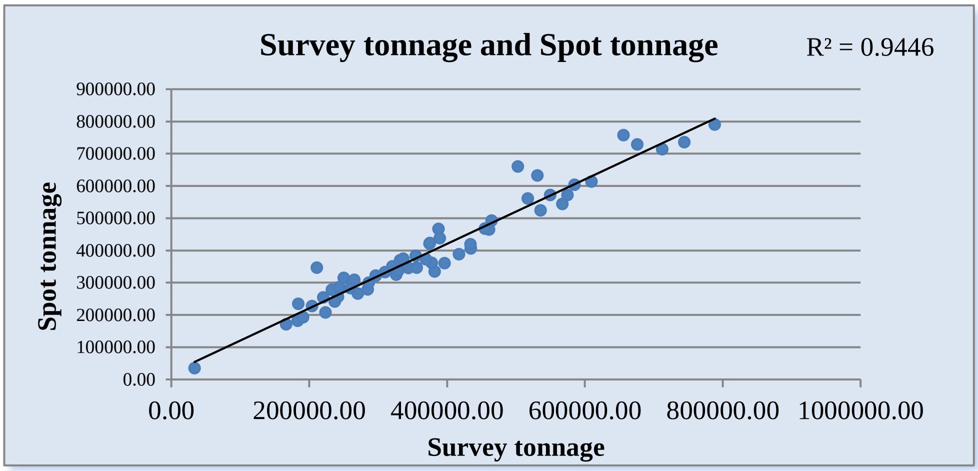


Figure 6.1 Linear relationship between survey tonnage and spot tonnage

(Source: Tetteh, 2014)

6.2.3 Scales

Static scales generally refer to platform scales, road, and rail weighbridges, hopper and bin scales as well as gantry (JKMRC, 2008). Generally, static scales provide a more accurate mass measurement and usually a preferred choice. According to JKMRC (2008), the precision of scales is between ± 0.05% to ±0.2% for platform scales; ±0.1 % to ± 0.5% for weighbridges and for gross load measurements; ±0.1%-0.25% for hopper or bin scales and ±0.15% - ±0.4% for gantry (JKMRC,2008: 82). Generally, the weighing of material that is in motion, for e.g. a truck that is in motion, is affected by the speed and acceleration of the truck or conveyer system. As a standard rule, when comparing mass measurements from various sources such as truck mass, mass measured by a static scale and that of a surveyor's measurement, the preferred choice of measurement is the surveyor's measurement.

6.2.4 Stockpiles, stocks, and inventory

Taking inventory of stockpiles is difficult to determine because of the uncertainties associated with volume measurement, bulk density as well as obtaining a representative sample to analyse metal content. Technologies such as laser scanners can determine the volume of stockpiles to about ±5% accuracy (JKMRC, 2008). Obtaining credible metal content is a challenge due to estimations with bulk density as well as sampling and analysis.

A significant mass of material is stored in plant stocks and stockpiles. Although the accuracy level required for mass measurement of plant stocks and stockpiles are unknown, it can be a major source of discrepancies in the mass and content measurement for accounting purpose. Stock measurements can be cross-checked by reducing the stock to zero. Plant stock is generally referred to as the feed product.

Stockpile measurements can be made to about an accuracy of (± 0.5%) using remote sensing technologies (laser scanning or photogrammetry) which results in 3D images (JKMRC, 2008). Variables such as bulk density and moisture content are however difficult to obtain from stockpiles. Bulk density is generally affected as the material undergoes compaction, oxidation, swelling, and ageing (JKMRC, 2008). Ideally, the mass measurement of process inventory should be free of any bias and with a random error that is within the limits of accuracy required for metal accounting purpose.

6.3 Metal accounting methods for in-process metal inventories

A typical material handling and processing unit consists of several units including mining truck, ore stockpile, conveyor/pipeline, concentrate stockpile, heap leach pad, oil tanks, flotation cell, and thickener (Figure 6.2). Each of these units would bear various characteristics in terms of the metal content. Some of these characteristics include the lower and upper bound of the metal content, spatial heterogeneity and the residence time of that particular unit in a day. Table 6.1 contains a classification of the main process units for metal accounting purposes. Each unit is described in terms of its lower bound, upper bound, spatial heterogeneity and time of residence.

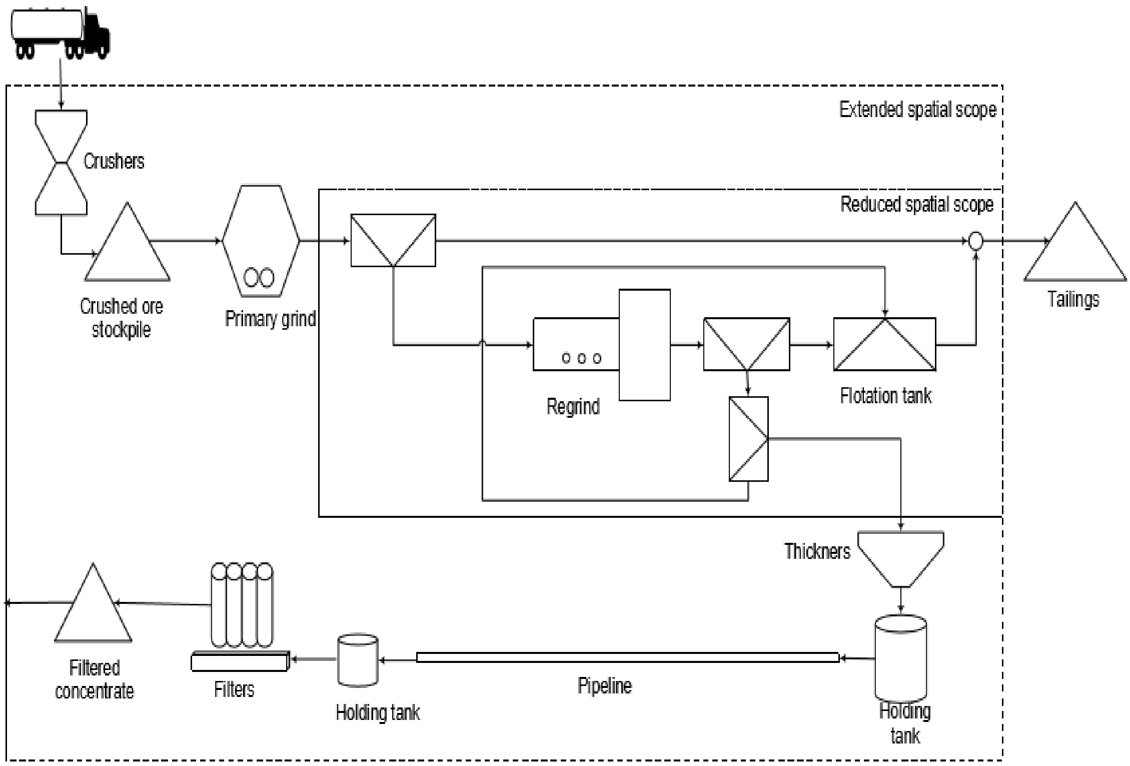


Figure 6.2 Generic plant flow sheet

(Source: Lachance et al., 2014)

Table 6.1 Characteristics of metal inventory units

Unit/section	Lower bound	Upper bound	Spatial heterogeneity	Residence time (versus a day)
Mining truck	Yes	Yes	High	Short
Crushers	Yes	Yes	High	Short
Crushed ore stockpile	Yes	No	High	Long
Primary grind	Yes	Yes	Medium	Short
Regrind	Yes	Yes	Medium	Short
Flotation bank	Yes	Yes	Low	Short
Thickener	Yes	Yes	Medium/high	Medium
Holding tank	Yes	Yes	Very low	Medium
Pipeline	Yes	Yes	High	Medium
filters	Yes	Yes	Medium	Short
Filtered concentrate	Yes	No	Low/medium	Medium/long
Tailings	Yes	No	Medium	Very long

Source: Lachance et al., (2013)

For the purpose of estimating the inventory in each of these units, a simplified plant flow sheet above (Figure 6.2) is used. Three different methods adapted from Lachance et al., (2013) and used for inventory estimations are the direct, indirect and redundant methods[34]. Each method can be applied to each of the processing units in Table 6.1. The metal in-process inventory accounting method based on current practice and adapted from literature Lachance et al., (2013) is illustrated in Figure 6.3. The

[34] Based on current practice and available literature

objective for each of these methods is to estimate the in-process inventory value represented by I (k) at the end of the k^{th} accounting period

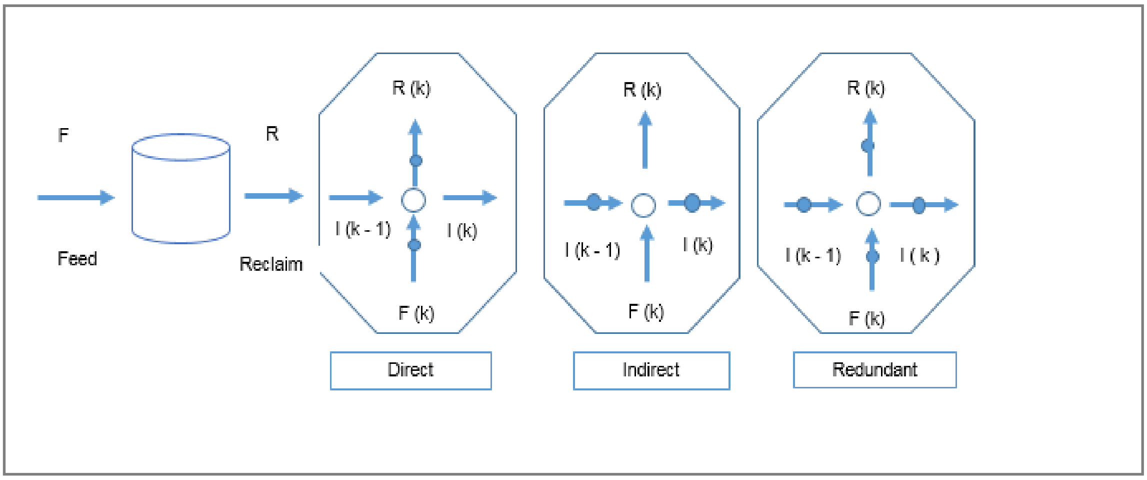


Figure 6.3 Metal in-process inventory accounting methods (Source: Lachance et al., 2014)

The general equation that represents all three metal inventory estimation methods is:

$$I(K) = I(K-1) + F(K) - R(K)$$

For example, if the accounting period is 30 days, then the inventory on the 30^{th} day would be equal to the inventory measured on the 29^{th} day plus the feed on the 30^{th} day minus the reclaim on the 30^{th} day.

According to Lechance *et al* (2014)., each of these accounting methods can be analysed through a simplified process unit as indicated in Figure 6.2. Lechance *et al* (2013)., further explained that two imaginative streams denoted by I(k-1) and I(K) represent inventory levels at the beginning and end of the k^{th} accounting period. The arrows in Figure 6.3 represent each stream whereas the dot on each arrow represents an available measurement (Lechance et al., 2014). Table 6.2 outlines the description and challenges associated with each of these methods.

Table 6.2 Methods for metal inventory measurements

Accounting method	Description	Challenge
Direct	Requires measurements of ore variables such as (dry ore mass, metal assay, wet ore mass, moisture content, density, etc.) to determine ore stockpile metal inventory.	The measurement of each of these variables comes with potential accuracy issues that need careful assessment. A typical example is when the spatial heterogeneity of an inventory unit (Table 6.1) related to high volumes makes it difficult to obtain a representative sample and hence carries uncertainty. A procedure for computing the metal inventory estimates using Monte Carlo methods/variance propagation methods to determine the actual value of the metal inventory and the standard deviations of a measured variable have been provided (Cutler and Eksteen, 2006).
Indirect	With this method, the metal inventory of a given process unit is estimated by subtracting the cumulative reclaim (R^2) from the cumulative feed (F).	This method results in poor estimation of errors over time and requires major adjustments to estimate the produce, which would likely impact on the financial performance.

Redundant	Uses both direct and indirect methods to reach redundant data set. (Lachance and Flament, 2011). The accuracy attributed to each measured variable can be assessed and possible detection of systematic errors. The advantage of this method is the use of redundant data sets.	The challenge with this method is the data processing approach involving data reconciliations (Bragajewicz, 2010). It also does not require additional datasets but makes use of available data that is stored in different reports.

Source (Adapted from Lachance et al., 2013; Lachance et al, 2014)

6.3.1 The metal balancing process

The metal accounting process can be thought of as a sequence of custody transfers of physical material (including ores, concentrates and metal ingots) usually accompanied by a transfer of value (AMIRA P754,2007). Typically, the material is transferred from an ore resource through the various stages until a metal product is formed. A similar process is realised for most industrial minerals and commodities. Table 6.3 explains the various forms of custody transfers of the physical material through various areas of the value chain.

Table 6.3 Custody and value transfer from ore resource model until metal product is delivered to customers

Area	Ore model/ representation/process	Measurement
1. Mine (Physical ore)	Mine reserve or resource model	Geostatistics model/core drill information
	Mining process	The number of trucks, truck/hopper Factor, block model assays, survey measurements, bulk density, and moisture measurements.
2. Custody transfer of physical material (ore/concentrate) to concentrator	Concentrator feed stockpile comminution and separation to rejects (Tailings); to concentrate (product)	Occasional surveys Sample and assays flow rates; density; moisture content assays
3. Custody transfer to Transport	Concentrate receipt Residues Reject solutions Slags	Certified masses; sample for moisture assays, sizing, etc. Masses, samples for assay Flows, samples for assay Masses, samples for assay
4. Custody transfer to a smelter	Concentrate receipt residues Reject solutions	Certified masses Samples for moisture Assays, sizing, etc. Masses, sample assay Flows, samples for assay

	Slags	Masses, samples for assay
5. Custody transfer to customers	Metal/matte	Certified masses Samples for many assays

Source: Adapted from (AMIRA P754A, 2007)

A question to consider as the custody is transferred throughout the various mining and metallurgical processes until the final product is delivered to the customer is the quality in each metal content and the quantity in each custody.

The metal accounting process provides the interface between the metal/commodity recovery operations and the financial and commercial hub of the company. Records of the mass and metal value must be done according to accounting standards/accuracy bearing in mind the key principles in the code such as (accountability, credibility, transparency, reproducibility, auditability, integrity, and security). According to the AMIRA code, the minimum period over which a metal accounting documentation should be retained is 15 years (AMIRA P754A, 2007). The code, however, recommends that in an ideal sense, the document should be retained permanently.

During a custody transfer from one operation to the other e.g. from a mine to a concentrator or from a concentrator to a smelter, it is a general practice that the mass, sample, and analysis of the receiver which is the concentrator and smelter are used. According to the code, when the same company transfers material, the system of “home and away” should be used. In this system, the receiving company and sending operations must independently weigh the sample and analyse the material.

Still with reference to the code, In the case of a custody transfer between independent operations such as (refinery, toll smelting, and metal purchase), the code requires that a contractual agreement is entered.

6.3.2 Metal balance reporting

The physical outcome of the metal balance across the various custody areas is usually written in a report. The report is usually used to assess the financial and technical performance of an operation. A technical report is usually done using the matrix structure similar to the one in Table 6.4. Reporting is done at regular intervals, usually per shift/monthly/yearly average.

Table 6.4 Technical report of a mining company

	ANGLOGOLD ASHANTI LTD													
	IDUAPRIEM GOLD MINE		SCHEDULE F1: FGO STOCKPILE MOVEMENTS								MONTH: DECEMBER 2010			
	2010		DECEMBER				2. QUARTER TO DATE				YEAR TO DATE			
			BUDGET	ACTUAL	DIFF	% DIFF	BUDGET	ACTUAL	DIFF	% DIFF	BUDGET	ACTUAL	DIFF	% DIFF
	F1 -ORE STOCKPILES													
	TOTAL FGO STOCKPILE													
1	OPENING BALANCE	tonnes	2 794 803		-2 794 803	(100.0%)	2 504 853	3 100 002	595 150	23.8%	994 759	2 691 957	1 697 199	170.6%
2	OPENING BALANCE GRADE	g/t	0.97		-0.97	(100.0%)	0.97	1.06	0.08	8.7%	1.04	0.98	-0.05	(5.3%)
3	OPENING BALANCE OUNCES	oz ('000)	87.098		(87.098)	(100.0%)	78.241	105.237	26.995	34.5%	33.111	84.886	51.775	156.4%
4	TOTAL MINED IN	tonnes	366 881		-366 881	(100.0%)	1 149 619	1 712 225	562 606	48.9%	4 137 651	3 974 926	-162 725	(3.9%)
5	MINED IN GRADE	g/t	1.13		-1.13	(100.0%)	1.56	1.56	0.00	0.2%	1.62	1.62	-0.01	(0.5%)
6	MINED IN OUNCES	oz ('000)	13.276		(13.276)	(100.0%)	57.612	85.996	28.384	49.3%	216.124	206.682	(9.442)	(4.4%)
7	TRANSFER TO/FROM OTHER STOCKPILES (ON / -OFF)	tonnes												
8	TRANSFER TO/FROM STOCKPILES GRADE	g/t												
9	TRANSFER TO/FROM STOCKPILES OUNCES	oz ('000)												
10	MILL FEED	tonnes	356 839		-356 839	(100.0%)	1 002 453	904 268	-98 185	(9.8%)	3 762 321	3 132 486	-629 834	(16.7%)
11	MILL HEAD GRADE (GRADE CONTROL)	g/t	1.37		-1.37	(100.0%)	1.73	1.89	0.16	9.3%	1.70	1.80	0.10	6.0%
12	MILLED OUNCES	oz ('000)	15.760		(15.760)	(100.0%)	55.861	55.061	(0.800)	(1.4%)	205.448	181.317	(24.132)	(11.7%)
13	ADJUSTMENTS	tonnes									-1 424 714		1 424 714	100.0%
14	ADJUSTMENTS GRADE	g/t									0.00		-0.00	(100.0%)
15	ADJUSTMENTS OUNCES	oz ('000)	(0.143)		0.143	100.0%	(0.015)	(0.000)	0.015	99.9%	(43.312)	(0.000)	43.312	100.0%
16	CLOSING BALANCE	tonnes	2 804 845		-2 804 845	(100.0%)	2 652 018	3 907 959	1 255 941	47.4%	2 794 803	3 534 397	739 594	26.5%
17	CLOSING BALANCE GRADE	g/t	0.94		-0.94	(100.0%)	0.94	1.08	0.15	15.5%	0.97	0.97	0.00	0.1%
18	CLOSING BALANCE OUNCES	oz ('000)	84.757		(84.757)	(100.0%)	80.008	136.172	56.164	70.2%	87.098	110.251	23.153	26.6%
19	SCATS STOCKPILE													
20	OPENING BALANCE	tonnes						298 057	298 057		520 929	295 365	-225 564	(43.3%)
21	OPENING BALANCE GRADE	g/t						2.76	2.76		1.84	1.82	-0.02	(1.1%)
22	OPENING BALANCE OUNCES	oz ('000)						26.444	26.444		30.778	17.264	(13.514)	(43.9%)
23	TOTAL MINED IN	tonnes	-17 403		17 403	100.0%	-50 860	9 129	59 989	117.9%	-67 068	32 015	99 084	147.7%
24	MINED IN GRADE	g/t	1.37		-1.37	(100.0%)	1.38	2.01	0.63	45.6%	6.60	7.23	0.63	9.5%
25	MINED IN OUNCES	oz ('000)	(0.769)		0.769	100.0%	(2.255)	0.589	2.844	126.1%	(14.235)	7.442	21.677	152.3%
26	TRANSFER TO/FROM OTHER STOCKPILES (ON / -OFF)	tonnes												
27	TRANSFER TO/FROM STOCKPILES GRADE	g/t												
28	TRANSFER TO/FROM STOCKPILES OUNCES	oz ('000)												
29	TONNES TREATED (Check in)	tonnes												
30	MILL HEAD GRADE (GRADE CONTROL)	g/t												
31	MILLED OUNCES	oz ('000)												
32	ADJUSTMENTS	tonnes	-17 403		17 403	100.0%	-50 860	112	50 973	100.2%	453 861	20 308	-433 553	(95.5%)
33	ADJUSTMENTS GRADE	g/t	0.00		-0.00	(100.0%)	0.00	0.00	0.00	374.2%	0.00	-0.00	-0.00	(411.3%)
34	ADJUSTMENTS OUNCES	oz ('000)	(0.769)		0.769	100.0%	(2.255)	0.024	2.278	101.0%	16.543	(2.304)	(18.847)	(113.9%)
35	CLOSING BALANCE	tonnes						307 073	307 073			307 073	307 073	
36	CLOSING BALANCE GRADE	g/t						2.74	2.74			2.74	2.74	
37	CLOSING BALANCE OUNCES	oz ('000)						27.010	27.010			27.010	27.010	
57	TOTAL FGO ORE STOCKPILE													
58	OPENING BALANCE	tonnes	2 794 803		-2 794 803	(100.0%)	2 504 853	3 398 059	893 206	35.7%	1 515 688	2 987 322	1 471 634	97.1%
59	OPENING BALANCE GRADE	g/t	0.97		-0.97	(100.0%)	0.97	1.21	0.23	24.1%	1.31	1.06	-0.25	(18.9%)
60	OPENING BALANCE OUNCES	oz ('000)	87.098		(87.098)	(100.0%)	78.241	131.681	53.440	68.3%	63.889	102.150	38.261	59.9%
61	TOTAL MINED IN	tonnes	349 478		-349 478	(100.0%)	1 098 759	1 721 354	622 595	56.7%	4 070 583	4 006 941	-63 641	(1.6%)
62	MINED IN GRADE	g/t	1.11		-1.11	(100.0%)	1.57	1.56	-0.00	(0.2%)	1.54	1.66	0.12	7.7%
63	MINED IN OUNCES	oz ('000)	12.507		(12.507)	(100.0%)	55.357	86.585	31.228	56.4%	201.889	214.124	12.235	6.1%
64	TRANSFER TO/FROM OTHER STOCKPILES (ON / -OFF)	tonnes												
65	TRANSFER TO/FROM STOCKPILES GRADE	g/t												
66	TRANSFER TO/FROM STOCKPILES OUNCES	oz ('000)												
67	MILL FEED	tonnes	356 839		-356 839	(100.0%)	1 002 453	904 268	-98 185	(9.8%)	3 762 321	3 132 486	-629 834	(16.7%)
68	MILL HEAD GRADE (GRADE CONTROL)	g/t	1.37		-1.37	(100.0%)	1.73	1.89	0.16	9.3%	1.70	1.80	0.10	6.0%
69	MILLED OUNCES	oz ('000)	15.760		(15.760)	(100.0%)	55.861	55.061	(0.800)	(1.4%)	205.448	181.317	(24.132)	(11.7%)
70	ADJUSTMENTS	tonnes	-17 403		17 403	100.0%	-50 860	112	50 973	100.2%	-970 853	20 308	991 161	102.1%
71	ADJUSTMENTS GRADE	g/t	0.00		-0.00	(100.0%)	0.00	0.00	0.00	370.8%	0.00	-0.00	-0.00	(511.5%)
72	ADJUSTMENTS OUNCES	oz ('000)	(0.911)		0.911	100.0%	(2.270)	0.024	2.294	101.0%	(26.769)	(2.304)	24.464	91.4%
73	CLOSING BALANCE	tonnes	2 804 845		-2 804 845	(100.0%)	2 652 018	4 215 032	1 563 014	58.9%	2 794 803	3 841 470	1 046 667	37.5%
74	CLOSING BALANCE GRADE	g/t	0.94		-0.94	(100.0%)	0.94	1.20	0.27	28.3%	0.97	1.11	0.14	14.7%
75	CLOSING BALANCE OUNCES	oz ('000)	84.757		(84.757)	(100.0%)	80.008	163.182	83.174	104.0%	87.098	137.261	50.162	57.6%

Source: Adapted from AngloGold Ashanti Basic Mining Equation (BME) Reports (2010)

6.3.3 Analysis of metal balancing

According to the AMIRA code, a metal balance should satisfy the check-in-check-out system. This is defined as "what comes into the operation, minus any internal accumulations, plus any drawdown from internal stock is sufficiently similar, i.e. within acceptable limits in mass and analysed components to what goes out as products, losses and rejects." (AMIRA P754A,2007; 17).

The check-in-check out system means that all streams/feed that goes into the processing plant are measured, sampled and analysed. According to the code, this standard procedure should be adopted by all mining operations. Any deviations from applying the check in check out system should, however, be written in an exception report which should be approved by the management of the company. Table 6.5 highlights several aspects of the code, such as check-in-check-out strategies based on the type of operation and the quality of the feed.

Table 6.5 Balancing strategies for different metallurgical operations

Type of operation	Examples
Type 1: High Grade / High-value feed Medium flow rates High-value product Significant plant inventory Weigh and sample all inputs: Check-In. Weigh and sample all outputs: Check out.	**Smelter, metal refinery** The strategy recommended is Check-in-Check out.
Type 2:	**Gold Operations**

Low-value feed – medium to high flow rates, often of coarse feed. High-value product. Low mass, high-value plant inventory. Weigh and sample product.	A recommended strategy is to reconstitute tailings at measured feed rate and production
Type 3: Low-value feed – medium to high flow rates Sampled after the primary grind. Low-value product – sampled as concentrate shipments. Low plant inventory. Conveyor weigh scale or weigh feeder for feed mass into plant An accurate sampling of fine tailings.	**Base Metal Concentrator** The recommended strategy is to mass balance feed analyses, concentrate analysis and tailings analyses at measured feed rate and production.
Type 4: The high tonnage of feed and products. Minor rejects. Low plant inventory. Sometimes direct shipment to the customer. Detailed product specifications. International standards for sampling and characterisation. Custody transfer mass will often be a draught survey or a train load-out weight.	**Coal Operation, Iron ore** A commodity sales contract will detail prices, penalties and acceptable measurements techniques for both producer and buyer. Recommended strategy is to weigh and sample feed and product streams.
Type 5: High value, low tonnage of feed. High-value products. Minor reject streams. Significant plant inventory.	**Precious metals refineries** The recommended strategy is to check in-check out.

Weigh and sample all inputs: Check-In Weigh and sample all outputs: Check Out	
Type 6: Low value, high tonnage feed. Minor rejects, usually based on particle size or density. Minimal plant inventory.	**Aggregates** A commodity sales contract will detail prices (based on tonnage and size specification). The recommended strategy is to weigh feed and product streams.
Type 7: Low grade, high tonnage feed. Residues remain in-situ in some cases. Very high, difficult to measure, process inventory. Non-steady state, two phase slow reaction kinetics.	**Heap Leach** Weigh, sample and analyse feed and product. Perform accurate solution balance. Periodic checks of heap solution inventories and heap residue metal contents.
Type 8: Medium to low value, high tonnage feed. Low process inventory. Require use of Mineralogical analysis. Products may be in bulk, bags or other containers.	**Industrial Minerals** May be treated as a commodity. May be produced as different grades. **Weigh feed and product streams.**

Source: Adapted from (AMIRA P754A, 2007: 77)

When applying the check-in-check out system, there is a likelihood of an imbalance due to measurement errors, sampling inaccuracies and error due to analysis and in some cases gains or losses that cannot be accounted for.

6.4 Recovery and accountability

The concepts of recovery and accountability are separate although related. It is important for these factors to be determined as they help in determining the performance of the metallurgical processes and also for the purpose of reliable forecasting and planning.

It should be noted that several formulae can be applied in determining the recovery and accountability parameters. The code, however, stipulates that the formulae that are used should be consistent during reporting. A further requirement of the code is to define the boundaries over which accountability and recovery are measured as well as the inputs and outputs. The formula for calculating Recovery (Actual) according to the AMIRA P754A, (2007) code, which is fundamental for the check-in-check-out system is:

1. $\text{Actual recovery}=\frac{\text{sum of all useful or desired outputs}}{\text{sum of all inputs}}*100\%\ldots\ldots\ldots$ Formula 1

Other alternative formula approaches/formulae used are:

2. $\text{Built-up Recovery (\%)}=\frac{\text{sum of all useful or desired outputs}}{\text{sum of all inputs}}*100\%\ \ldots$ Formula 2

3. $\text{Theoretical Recovery (\%)}=\frac{\text{metal input-metal in losses}}{\text{metal input}}*100\%....$ Formula 3

It should be noted that whenever recovery is used, it should be qualified by the formula or approach and boundary of the recovery. The code further instructs that whenever a different formula is used apart from formulae 1, 2 and 3, it should be justified in an exception report and approved by the management in terms of the code (AMIRA P754, 2007).

The formula for accountability is given by (AMIRA P754A, 2007) as:

$$Accountability\ (\%) = \frac{sum\ of\ all\ outputs + stock\ and\ inventory\ change}{sum\ of\ all\ inputs} x100\%$$

According to the AMIRA P754A, (2007) code, similar to the recovery (%) parameter, the accountability parameter should also be defined in terms of boundaries. The accountability parameter also determines whether the input, output and stock changes parameters reconcile over time. The alternative formula for calculating accountability is:

$$2.\ \ Accountability\ (\%) = \frac{sum\ of\ all\ inputs + closing\ stock}{sum\ of\ all\ inputs + Opening\ stock} * 100\%$$

The major difference between the formula (1) and (2) are outlined in Table 6.6.

Table 6.6 Difference between accountability 1 and accountability 2

Accountability (1)	Accountability (2)
Gives no recognition for dormant process stocks.	Gives accountability (100%) for dormant stocks.
The use of Accountability is required in terms of the code.	If dormant stock is huge in relation to the throughput, for a particular accounting period, then accountability (2) formula brings it close to 100%.

Source: Compiled from (AMIRA P754A, 2007).

The plant stock and process inventory are defined in the code. The plant stock is defined as:

“*material received by a plant from previous processing operation but which has not entered a process stream, or any material produced by that plant to dispatch standard quality but not yet dispatched. A* process inventory is defined as *any material which has entered the process stream, but which has not yet been produced as a product for treatment in the next process” (AMIRA, 2007:76).*

Because there are several types of metallurgical operations, different strategies (discussed in Table 6.5) are employed to handle the metal accounting system.

6.5 Mine to mill reconciliation

AMIRA (2007:447) defines reconciliation as a “metallurgical balance which relates the production of saleable and rejects or waste materials from a process back to its source as ore or other feed material. This should be provided with defined stated errors as for any other metallurgical balance.

A generic model for performing mine-mill reconciliation is illustrated in Figure 6.4.

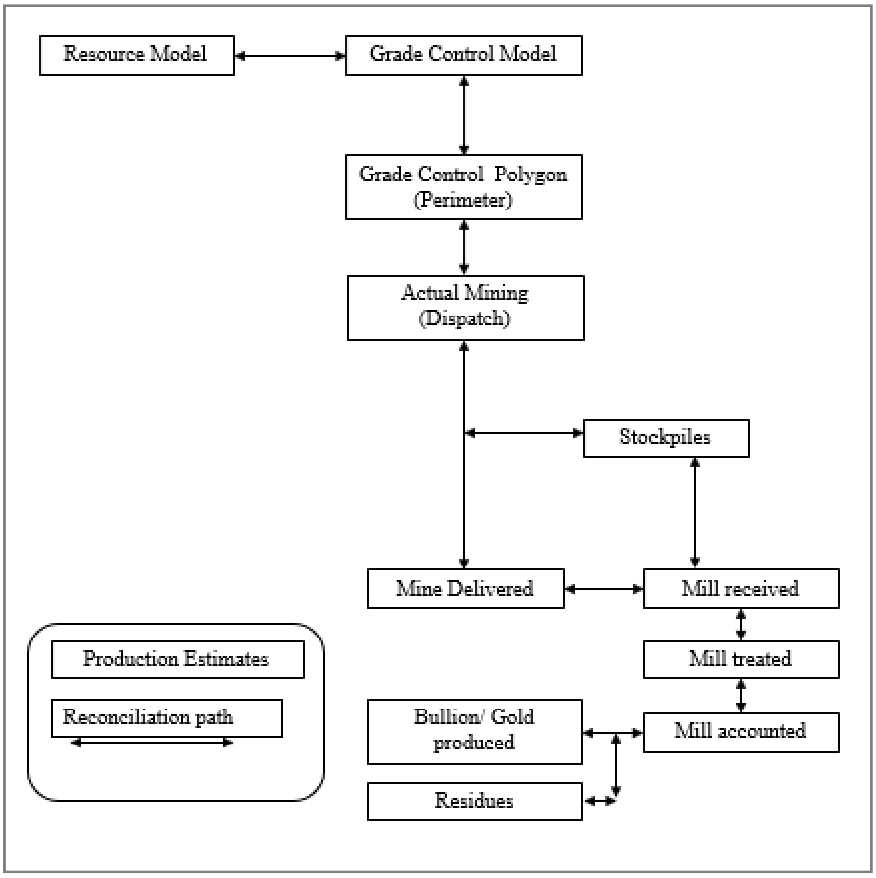


Figure 6.4 Model for mine to mill reconciliation (Source: Researcher's concept adapted from JKMRC, 2008)

In a typical mine to mill reconciliation process, measurement points are established between two of the points and reconciliation factors are determined. For e.g. reconciliation factors expressed in terms of percentages are determined between the grade control model and the resource model This point is illustrated in Figure 6.5, where reconciliation factors between the grade control model and reconciliation model for tonnes, grade and ounces are all within acceptable percentage margins (Tetteh, 2014).

GRADE CONTROL Versus RESOURCE RECONCILIATION - 2009 & 2010									
MONTH	GRADE CONTROL			RESOURCE			RECONCILIATION FACTORS (%)		
	Tonnes	Grade	Ounces	Tonnes	Grade	Ounces	Tonnes	Grade	Ounces
JAN 09	166134	1.91	10201.94	194309	1.88	11744.69	85%	102%	87%
FEB 09	264900	1.92	16325.2	294821	1.71	16208.59	90%	112%	101%
MAR 09	479133	1.85	28528.38	494701	1.75	27860.74	97%	106%	102%
APR 09	347613	1.88	21062.24	379302	1.79	21784.98	92%	105%	97%
MAY 09	258141	1.81	15024.76	281328	1.72	15553.04	92%	105%	97%
JUN 09	255475	1.72	14153.42	293871	1.52	14340.19	87%	114%	99%
JUL 09	271645	1.31	11399.99	317031	1.25	12750.75	86%	104%	89%
AUG 09	209082	1.20	8058.298	224290	1.09	7873.425	93%	110%	102%
SEP 09	409498	1.80	23663.14	431686	1.64	22784.54	95%	109%	104%
OCT 09	734061	1.85	43646.55	732762	1.75	41198.98	100%	106%	106%
NOV 09	367505	1.91	22576.68	410884	1.66	21893.89	89%	115%	103%
DEC 09	464245	1.72	25661.71	444023	1.66	23755.67	105%	103%	108%
JAN 10	357378	1.70	19538.97	365382	1.47	17259.93	98%	116%	113%
FEB 10	247638	1.72	13672.17	275195	1.62	14319.88	90%	106%	95%
MAR 10	222457	1.84	13161.7	221644	1.64	11683.95	100%	112%	113%
APR 10	514600	1.69	27959.93	529056	1.60	27221.58	97%	106%	103%
MAY 10	584872	1.76	33020.92	606080	1.57	30664.06	97%	112%	108%
JUN 10	610114	1.61	31593.43	663867	1.47	31330.43	92%	110%	101%
JUL 10	197177	1.89	11983.66	214021	1.51	10400.38	92%	125%	115%
AUG 10	21754	2.34	1636.612	26952	2.21	1915.023	81%	106%	85%
SEP 10	326471	1.79	18741.79	382069	1.68	20641.87	85%	106%	91%
OCT 10	322835	1.76	18227.4	368571	1.74	20560.36	88%	101%	89%
NOV 10	567583	1.83	33438.57	633692	1.71	34906.6	90%	107%	96%
DEC 10	432780	1.65	22918.97	422577	1.63	22152.85	102%	101%	103%
TOTAL/AVERAGE	8633091	1.75	486196.4	9208114	1.62	480806.4	94%	108%	101%

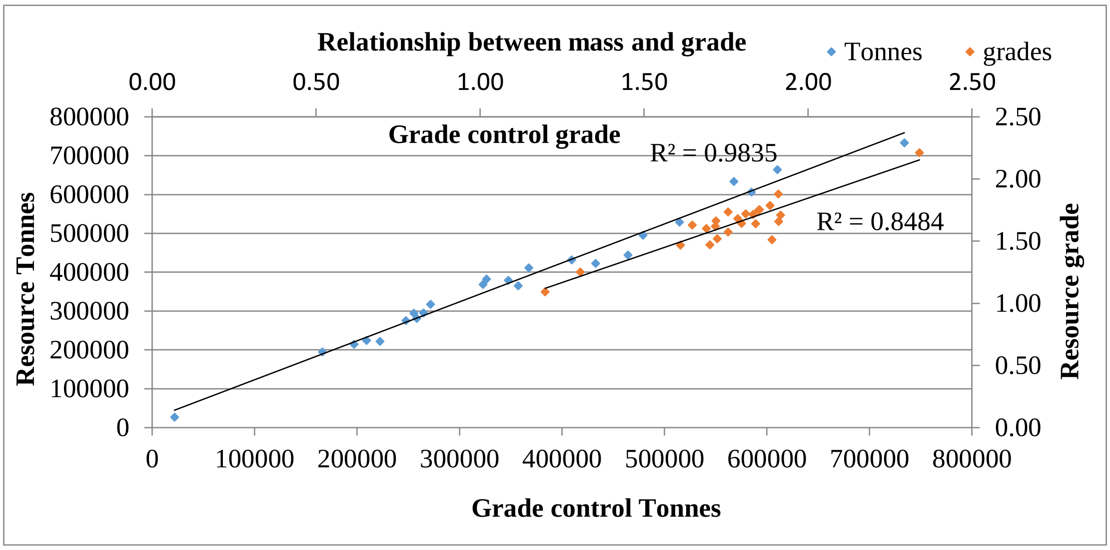


Figure 6.5 Grade control versus resource model (Source: Tetteh, 2014)

The reconciliation factor (percentage) calculated in Figure 6.5, compares the quantity and quality estimates between the grade control model and the resource model. A strong relationship exists for both tonnage and grade at that measuring point and therefore it can be said that the grade control and resource models are reliable (R^2 = 0.98 for tonnes and R^2 = 0.85 for grade).

According to the AMIRA P754A (2017) code of practice, the following factors should be considered when performing an effective mine to mill reconciliation:

1. A clear audit trail and process transparency should be ensured in order to make the adjustments of production estimates clearer;
2. The process should account for errors in selection and misclassification;
3. Stockpile inventories should be measured and not used to absorb discrepancies over time;
4. Avoid using factors such as moisture contents truck/loader factors, densities to cover production estimate discrepancies through unjustified adjustment;
5. The use of factors such as the MCF for predicting future mine to mill production estimate discrepancies; and
6. Adjusting production estimates in the mine – mill process of mine-mill reconciliation discrepancy.

Some key elements that lead to a credible mine to mill reconciliation program is to undertake the following steps (JKMRC, 2008).

1. Capturing the data;
2. Handling the data;
3. Validation;
4. Analysis;
5. Adjustment; and
6. Reporting in a manner that is transparent to those interested.

The method used for mine-to-mill metal accounting and reconciliation must also be auditable so that the source of production figure adjustments and key performance indicators can be traced. An effective reconciliation practice requires a diligent approach to production and inventory measurements.

Due to significant differences between production measurements and metal accounting methods in the mine and metallurgical process, personnel from the mines and metallurgical departments meet once a month to compare production figures for that accounting period. This usually results in dispute because measurement and estimation approaches between the two departments are different. Although adjustments to production figures may be required for the sake of consistency, this may affect bonuses or production targets of a particular department.

6.6 Conclusion

This chapter explained the real-time material tracking with specific reference to in-process metal inventory measurement methods. Three methods namely direct, indirect and redundant methods were discussed. The direct method requires an accurate measurement of the ore variables such as dry mass, metal assay, wet ore mass, moisture content and density to determine ore stockpile metal inventory. The challenge with the direct method is that each of the variables described previously comes with a potential accuracy issue whether it is mass measurements or sampling and assaying for content grades. The direct method needs careful assessment of all the variables.

With the indirect method, the metal inventory of a given process unit is given by subtracting the cumulative reclaim from the cumulative feed. The challenge with this method is that it results in the poor estimation of errors over time and requires major adjustments to estimate the produce. These adjustments are likely to impact the financial performance of the company. The redundant methods use both direct and indirect methods to reach a redundant data set.

Due to the redundant data set, the accuracy attributed to each measurement variable can be assessed and possible detection of systematic errors. The challenge with the redundant method is the data processing approach involving data reconciliations (Bragejeodzgaua, 2010). Based on the three methods of process inventory measurements discussed in this chapter, the preferred method for implementation is the redundant method, because it uses both direct and indirect methods. Also the accuracy for all the measurement variables can be assessed as well as the detection of systematic errors.

The next chapter focusses on the development of a conceptual framework for real-time tracking of metal content from in-situ to plant entry/surface. The chapter would also apply the Theory of constraint (TOC) and Scrum flow techniques to identify bottlenecks in the ore flow process. The objective is to identify and eliminate human errors during the accounting process.

7 Case study: Real-time material tracking

7.1 Introduction

The previous chapter discussed real-time material tracking of volume and in-process inventory measurements. Based on the three methods of process inventory measurements discussed, the author concluded that the preferred method for implementation is the redundant method, because it uses both direct and indirect methods. Also, the accuracy for all the measurement variables can be assessed and the detection of systematic errors.

This chapter discusses a typical ore flow in an underground mine with critical measurement points using a typical mechanised mine as a case study. At every critical measurement point, variables such as mass, grade, fragmentation, moisture content and location-based data can be measured, monitored, and tracked. The application of data processing techniques and tools such as six-sigma and lean process improvement methodology are discussed. The thinking process of the theory of constraints and its application in the mining industry are also discussed. Operational bottlenecks identified in the production value chain was developed. A system solution known as the production flow solution for dealing with bottlenecks in a production shaft system was also discussed.

7.2 Ore flow in underground mechanised operation

The Rustenburg platinum operations are located in the North-West province, which is north-east of the town Rustenburg and Kroondal. The operation is 126km and 123km north-west and east of Johannesburg and Pretoria respectively (Figure 7.1).

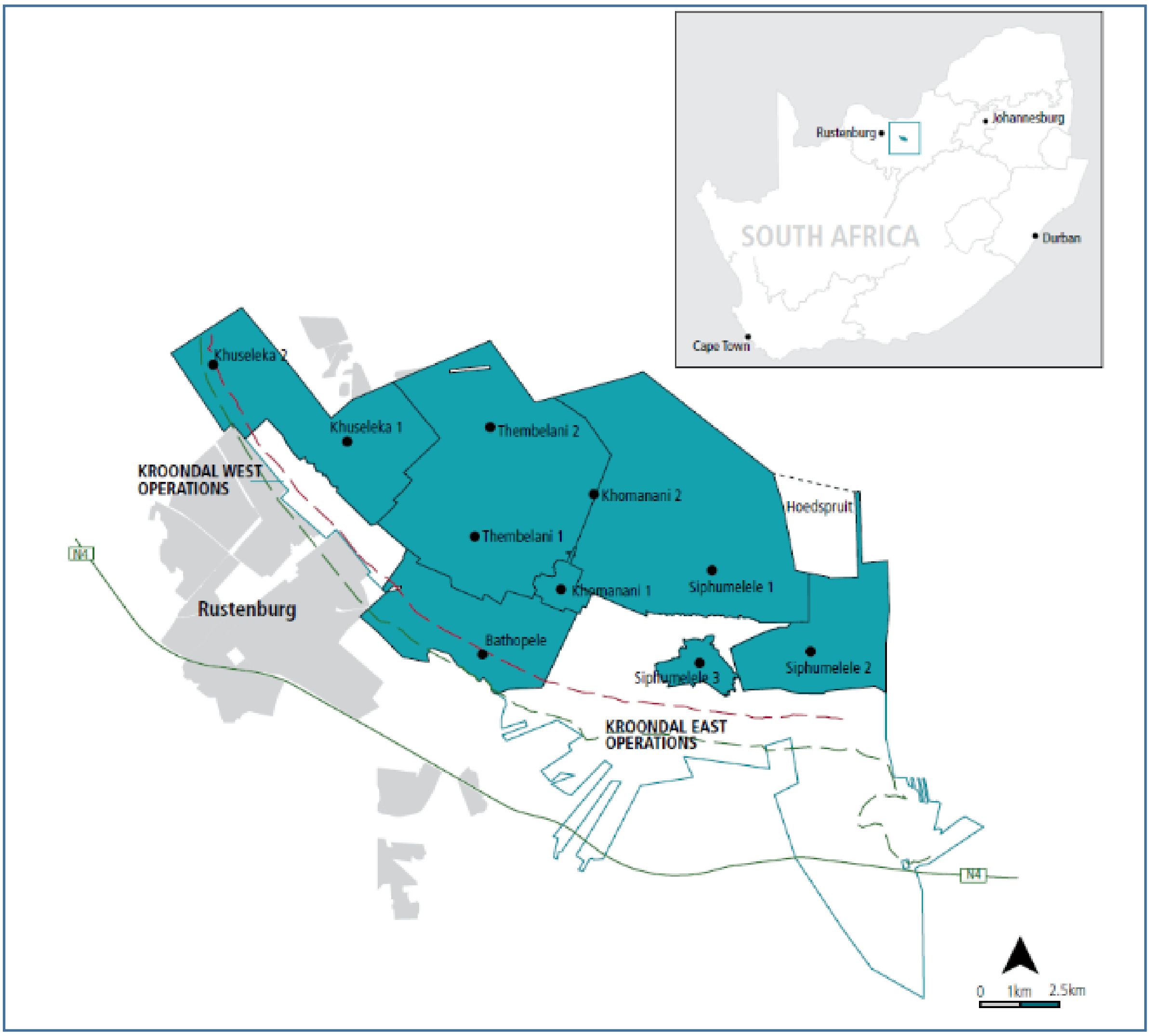


Figure 7.1 Platinum operations at Rustenburg (Source: Adapted from Sibanye-Stillwater, 2019)

There are three conventional operating shafts namely Siphumele, Kuseleka and Thembalani as well as a mechanised operation which will be referred to as Mine A. At Mine A, the mineral resource is accessed from the surface using two declines which are at an approximate depth of 500m. The expected production at Mine A is about 280 000 tonnes per month. The Mine A platinum forms part of the Western Limb of the Bushveld complex. The mine extends over an area of about 17km^2. The mining method is a bord and pillar mining layout at the low-profile section and breast mining layout at the central low-profile section. The ore transportation from underground to surface is through a conveyor belt. Ore is hoisted from the East and Central shafts into a Silo on the surface and poured out from below the silos and stockpiled on the surface as shown in Figure 7.2. The stockpiled ore on the surface is tipped onto an overland conveyer and poured into a second silo - also on the surface. Ore flows through the Second Silo onto a conveyor and then sent to the mill for processing. The ore is further concentrated and refined at Rustenburg's Platinum mines metallurgical facility. Typical critical measurement points at which measurement, monitoring and tracking of the ore variables are also indicated in the ore flow diagram in Figure 7.2. These critical measurement points (in Figure 7.2) are critical-measurement-one (CM1), critical-measurement-two (CM2), critical-measurement-three (CM3), critical-measurement-four (CM4), critical-measurement-five (CM5), critical-measurement-six (CM6), and critical-measurement-seven (CM7). At every critical measurement point the ore variables such as the tonnage, product content, fragmentation, density, moisture content, and location can be measured, monitored and tracked. Various production data obtained from each critical measurement point and analysis applicable at the critical point would be discussed in subsequent sections.

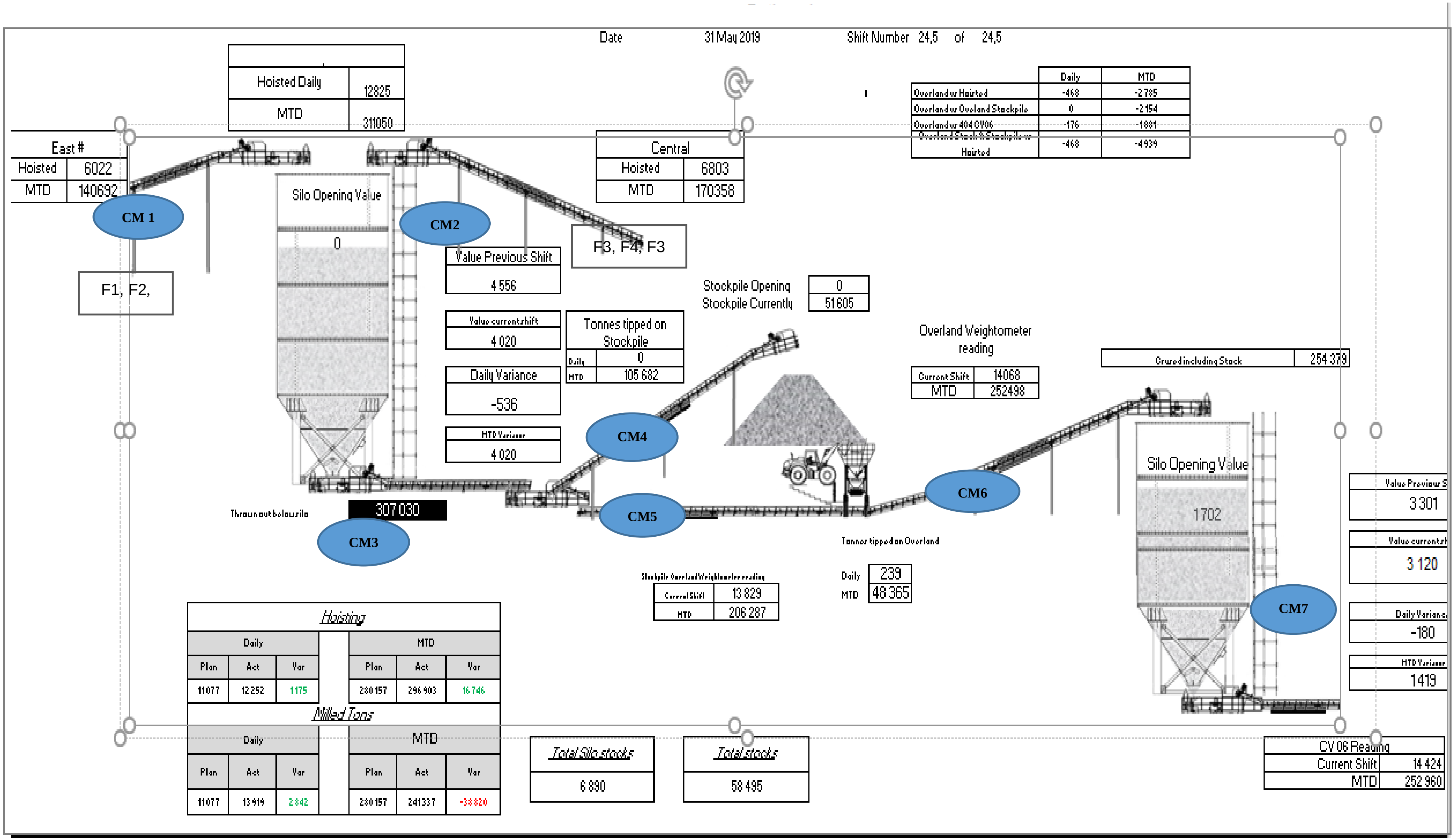


Figure 7.2 Mine A surface ore flow movement

(Source: Adapted from Mine A ore movement, 2019)

7.3 Data processing and presentation

Several data are collected from an operating underground mine. Some of these include location-based data, sampling, and analyses for grade or content, density, tonnage, moisture content and fragmentation for sizes of blasted material. Systems engineering practitioners and engineers, in general, apply various systems thinking tools to ensure the various components of the system works at its best. Process quality improvement methodologies such as six-sigma, lean process improvement methodology which are applicable in the analysis of production data would be discussed in subsequent sections.

7.3.1 Six-Sigma methodology

The six-sigma methodology applies a disciplined approach in managing projects, solving problems, improving performance and leveraging information (iSixSigma, 2019). The main concept of the six-sigma model is depicted in Figure 7.3.

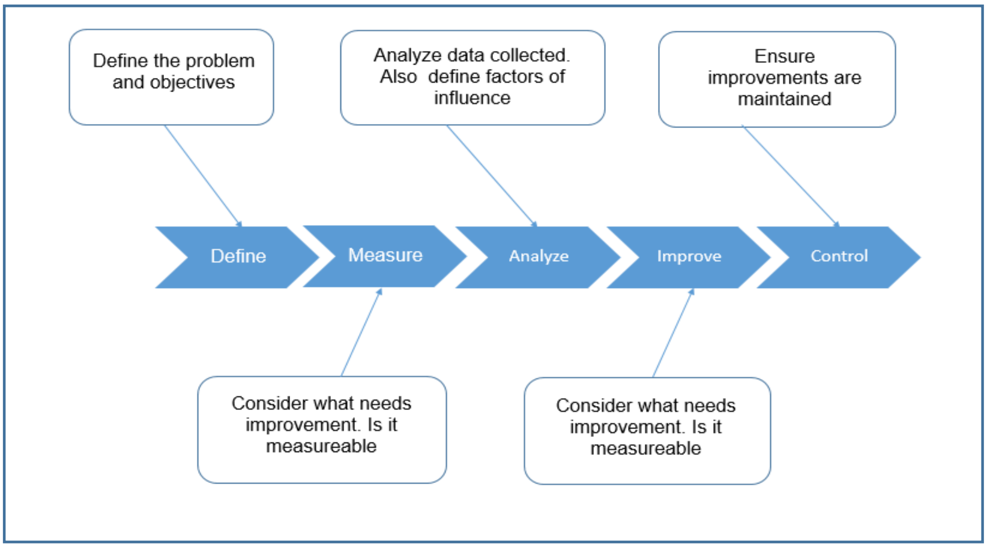


Figure 7.3 Six-sigma model (Source: Adapted from Grey campus, 2019)

At the define phase, the problem that needs to be solved is clearly defined and project team members are informed. The measurement phase confirms who the customer is, determines which metric needs to be improved, what the performance standards are, the units of measurements and validation of the measurement system used to track the performance metric that needs to be improved. The analysis phase ensures improvements are maintained and also creates an environment of continuous improvement. The improvement phase determines, validates and implements solutions to achieve the goal statement. Several case studies have been undertaken using the Six-sigma process improvement methodologies. Some of the basic tools used in Six-sigma include:

1. Check sheet: Check sheets are used for the data collection on the frequency of problems during a production process as well as other processes. It is also used as a standard for a list of activities. Its function is to present information in an efficient, organized and graphical format. Data collection is important because it is necessary for statistical analysis. The data collected can be converted into a Histogram, Pareto diagram, or a Bar chart. Various check sheet samples are created and used in the mine.
2. Histogram: Histograms are used to understand the nature of data. It comes in the form of a bar chart that determines the frequency distribution of a data set. Figure 7.4 depicts a histogram developed for a stoping analysis year to date graph at Mine A mine.

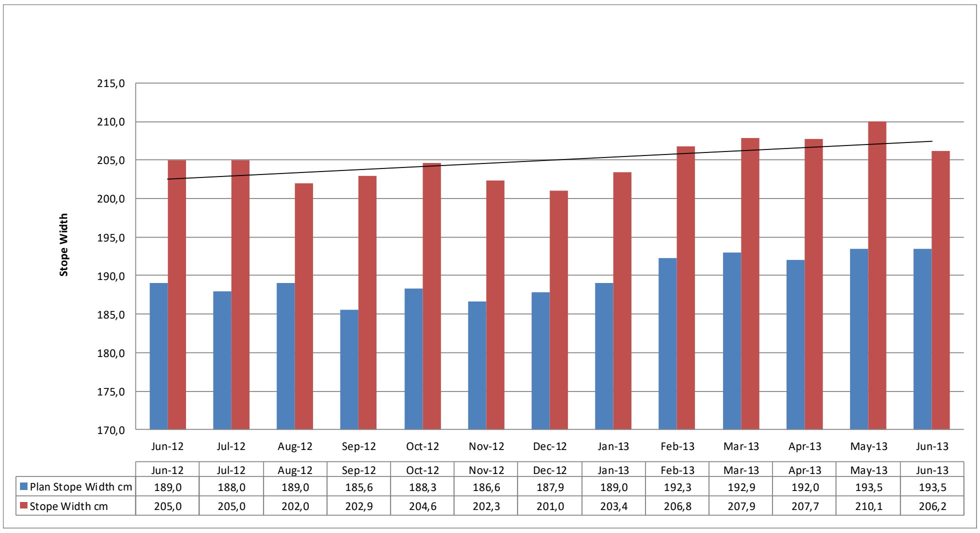


Figure 7.4 Histogram diagram
Source: Adapted from (Mine A ore movement file, 2019)

3. Cause and effect diagrams: Also known as the fishbone diagram. This tool is used to explore the causes and effects of a single effect through brainstorming. The causes are categorised under 6M[35]. An example of cause and effect diagram is illustrated in Figure 7.5.

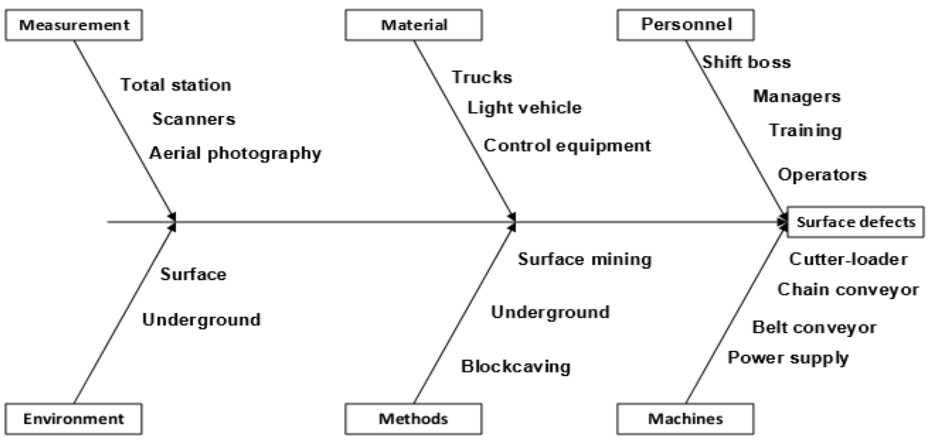


Figure 7.5 Cause and effect diagram (Source: Researcher's concept, 2019)

[35] M means: Man, Material, Method, Machine, Measurement, and Mother Nature.

The diagram in Figure 7.5 depicts the effect of a surface defects (e.g. irregular readings at critical measurement point) at Mine A and their causes. These causes can be classified under the 6Ms known as measurement, material, man, mother nature, methods and machine.

4. Flow chart: Used to depict the process flow in upstream and downstream processes. Figure 7.6 below depicts a flow chart. Each of the symbols in the flow chart represents an action.

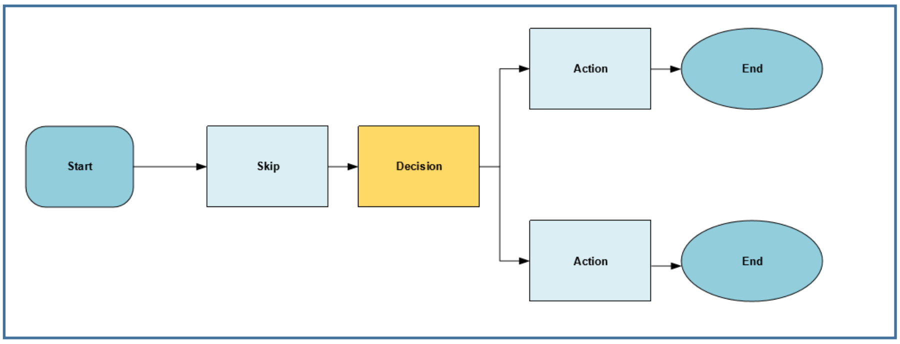


Figure 7.6 Flow chart
(Source: Adapted from Smartdraw, 2019)

5. Scatter plot: A scatter plot shows the relationship/correlation between the two variables. The relationship is either positive or negative. Figure 7.8 is a scatter plot generated for the relationship between assays for Au duplicate values and Au original values.

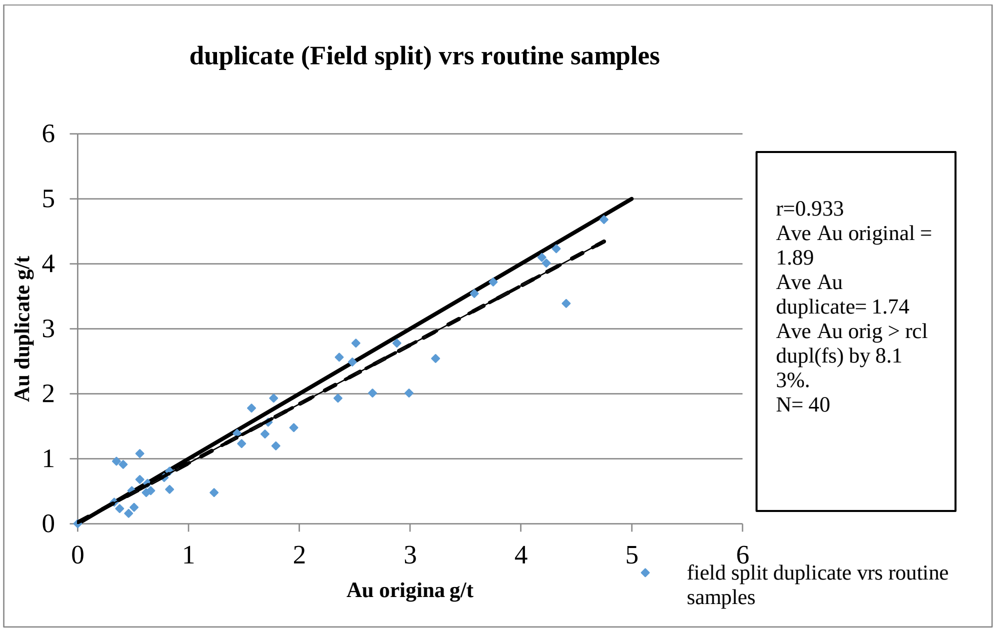


Figure 7.7 Scatter plot and correlation diagram
Source: Adapted from (Tetteh, 2014)

6. Control chart: Control charts are used to check whether process data remains under control. A process control limit is used to compare operational ranges over a shorter period of time. The process data is therefore analysed to remain within the process control limits. Figure 7.9 depicts a control graph grade analysis.

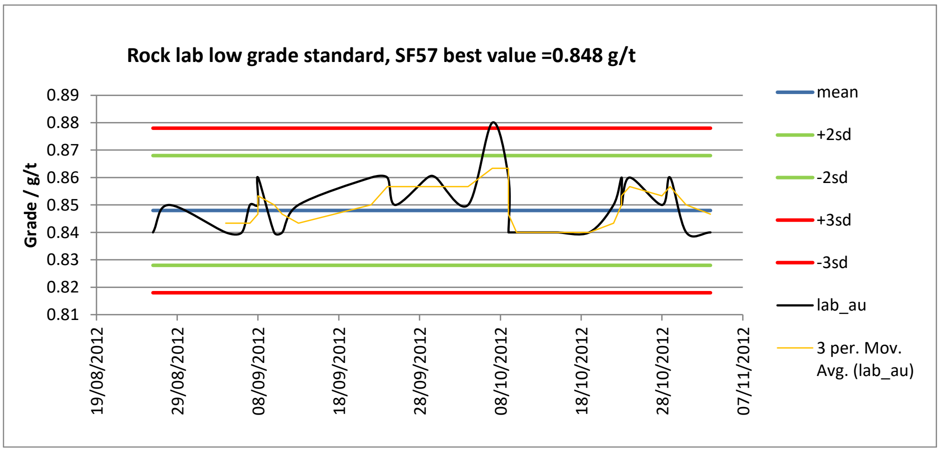


Figure 7.8 Control graph grade analysis
Source: Adapted from (Tetteh, 2014)

The next section explains the lean process improvement methodology as applied in various operations including mining.

7.3.2 Lean process improvement methodology

The lean process improvement focuses on the continuous improvement of a process by eliminating wasteful practices and improving efficiency. The lean process focuses more on customer satisfaction. A formal definition of lean according to Dunstan et al., (2006) is the constant elimination of waste. The actual practice of lean relies on (Dunstan et al, 2006):

- Engaging workplace leaders;
- Encouraging employees to fix agreed standards for their workplace;
- Empowering employees to write their own standards and improve them;
- Visual representation of key production performance data and comparing employees at a junior level to make operational decisions that are data-driven;
- Creation of production and manufacturing teams; and
- Application of business improvement tools.

Although the lean process is rooted in the manufacturing industry, it has been successfully applied in the minerals processing and mining business. The lean process improvement methodology was applied at Rio Tinto's Weipa Bauxite and aluminium mines located in Australia (Dunstan et al, 2006). A combination of lean and six-sigma techniques are applied in the theory of constraint (TOC). The next section is the application of the thinking process of TOC using a typical underground mine (conventional and mechanised) as context.

7.4 The theory of constraint

Goldratt (2010) defines a constraint as anything that limits a system from achieving higher performance with respect to the objective of that system. It is based on a thinking process that enables people to invent simple solutions to complex problems. According to Goldratt (2010), the theory is based on the principle that in every system, there is a constraint/bottleneck that prevents the system from functioning at its best. The focus of TOC is outlined in the steps below (Goldratt, 2010):

- The overall system with focus on what to change instead of how to change.
- TOC also focuses on increasing the throughput of the system and leveraging fixed costs instead of cutting cost or minimising variability.
- TOC focuses on a change that will make the most positive difference instead of lots of small changes.
- TOC principle believes in the use of the least expensive improvement options before the expensive options.
- Rather than planning for perfection, TOC believes in the use of buffers to deal with uncertainty.

TOC uses a 5-step approach for continuous improvement of business operations known as the five focusing steps. These steps are outlined in Table 7.1.

Table 7.1 Five focusing steps of TOC

Step	Description
1. Identifying the system constraint	This is what prevents the system from generating income at a faster rate. It can be a physical component such as particular equipment or a policy (policy constraint is amongst the commonest). An example of a possible constraint is called the wandering constraint. It is better to address policy constraints before the physical ones.
2. Exploiting the constraint	This requires that all effort is made to get the most out of the constraint. For example, if a machine in the manufacturing process is the constraint, then the machine should be exploited.
3. Subordinating everything to the constraint.	This means to fully exploit the constraint, a number of other processes need to be re-oriented so that time is not lost at the constraint. E.g. If a machine operates for more time, it may be necessary to order more parts of that machine or improve the upstream and downstream processes. An example is the additional operator duties that are not associated with the constraint or searching for alternative routes for some of the products.
4. Elevation of the constraint	This means that after all the options have been exhausted, additional capacity should be added. From the previous example in step 3, it means that a machine should be purchased.

5. When the constraint is broken, return to step 1.	This may happen before step 4.

Source: Adapted from (Goldratt, 2010)

The application of these steps would enable the design of a system that can operate at its best, in terms of a high degree of reliability as well as producing the highest output levels possible. The steps and its application in mining using a typical underground mine as context would be discussed in subsequent sections.

7.5 Identification of potential bottlenecks in the ore flow system

There are several operational constraints that exist in a typical production flow. Although the constraints listed below are industry generic, Goldfields South deep and Lonmin Rowland mine shaft identified a number of constraints listed in Table 7.2.

Table 7.2 Mine operations constraint

	Operational Constraint
1	Transporting employees through the shaft system to their workplaces and back
2	Machine location management
3	People location management
4	Realtime environmental condition monitoring
5	Backlog on backfill of stopes - New stopes are delayed which impacts on effective face time
6	Backlog on the secondary support
7	Drilling not performing to optimal - low rate of advance - Impact on effective fact-time
8	Shotcrete placement rate and backlog - Impact on effective face-time
9	Internal logistics and material cart turnaround time - Impact on enabling logistics
10	Lack of critical stock items close to the workplace

11	Lack of labour buffer mitigating the risk of lost blasts due to non-availability of employees
12	Inefficient recruitment lead time

Source: multiple sources (Adapted from South Deep mine and Rowland Mine shaft-Marikana-Lonmin)

Some of the typical constraints from Mine A's perspective include a vertical shaft that cannot handle material coming from belt level; a plant whose design capacity is not big enough to handle the material coming in; a box-hole that can't handle the material coming in; a level in which the number of locomotives can't handle materials coming inside. The final framework which would be discussed in the new knowledge chapter (chapter 8) would enable an understanding of the need to measure the impact of discrepancies. The next section explains a typical application of the TOC known as the production flow solution.

7.6 Production flow solution

The production flow solution focuses on managing the identified bottlenecks as well as protecting them by increasing capacity and providing buffers. When buffers are placed around the bottleneck constraints, the entire system is decoupled from that of the constraint and therefore all attention can be focused on that bottleneck. The Scrum production flow principle is applied daily in the production flow meeting where there is an adaptation of Scrum (software project management) and production flow (TOC and lean techniques). The Scrum production technique takes into account how the world and people work and makes every detail of an entire operation visible so that the entire operational team can view what is happening (Mabote, 2016). In a typical operational environment like mining, a problem in one area would have effects on the other parts of the operation. Intensive planning is required, the execution of plans requires quick and accurate decisions to be made by those who are close to the action. The entire flow of the production operation can be viewed holistically using colour patterns of the flow over time and therefore we can determine within seconds which of the areas of the operation and department requires immediate attention (Figure 7.9). The Scrum production flow room is a meeting place (involving the heads of the various mining departments, middle managers and selected employees). At this meeting place, a visual information on the current status of the entire operation are discussed. The flow room provides a forward view and patterns of areas that require more attention. Teamwork is very crucial to achieving a successful flow room. The flow room also gives each worker visual feedback on their responsibilities and how their actions affect the overall system and the outcomes.

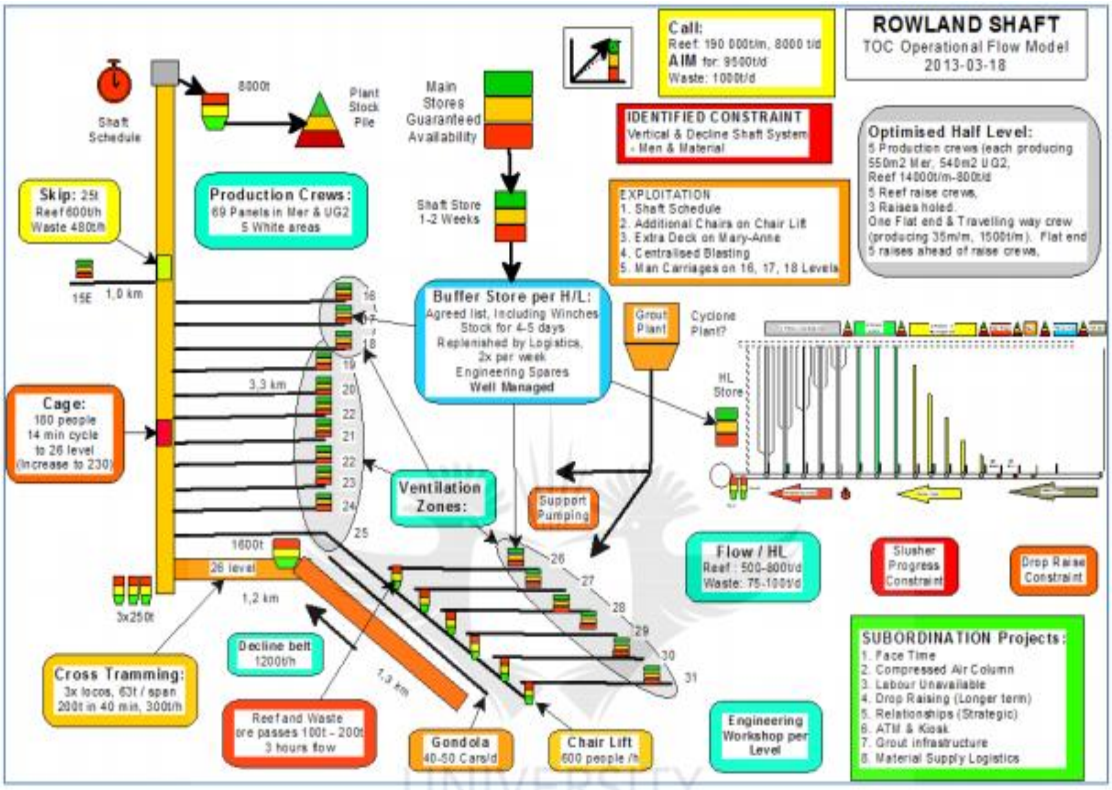


Figure 7.9 Mine shaft analysis diagnostic picture
Source: Adapted from (Mabote, 2016)

7.7 Conclusion

This chapter provides a case study for real-time material tracking in a typical mechanised underground mine. Critical measurement points where measurement variables like tonnage, grade, product content, fragmentation, density, moisture content, can be measured, monitored and tracked were depicted in Figure 7.2. Various data processing and presentation techniques, including the Six-Sigma methodology, the lean process improvement and the TOC process improvement approaches were discussed. Basic tools used in Six-Sigma include a check-sheet, histogram, cause and effect diagram, flow chart, scatter plot, and control graph. In summary, the lean process improvement methodology focusses on improvement of a process by eliminating wasteful practices. The TOC is based on a principle that in every system there is a constraint/bottleneck that prevents the system from functioning at its best. A five-step thinking process was developed in the TOC approach to enable the invention of simple solutions to complex problems. In terms of identifying operational bottlenecks in an ore flow system, some of the constraints identified was listed in Table 7.2. A specific application of TOC known as the SCRUM production flow system developed by Mabote (2016) was discussed. In this production flow system, the entire flow of the production operation can be viewed holistically using colour patterns of the flow over time (Refer to Figure 7.10). This makes it possible to determine at a glance which areas within the operation require immediate attention.

The author recognizes that teamwork is crucial in achieving a successful flow in every system. An understanding of the responsibilities of each worker and the impact of their decisions and actions should be made clear. The discussion of this case study has limitations in terms of the data verification and analysis of the data. These would be addressed in the next chapter which puts everything together into a framework.

8 Time and spatial tracking of metal content from in situ to plant entry: A digital mining technology approach

8.1 Introduction

The previous chapter is a case study on the identification of critical measurement points for a typical underground mechanised mine. Various data processing, presentation tools and techniques were outlined. The limitations in the previous chapter are in terms of data verification and reconciliation of discrepancies. This chapter proposes a conceptual framework for ore tracking as a solution to this limitation. The framework for this solution is outlined in Figure 8.1. The variable of interest is first measured. The discrepancy in terms of what is planned and expected is then determined. The impact of the discrepancy has to be determined and the risk assessed. A significant question would be an acceptable level of discrepancy. The tolerance limit for each measurement variable is required to enable an assessment of the measurement's compliance to existing protocols. A decision is then made in terms of the acceptance or rejection of the measurement variable (for example calibrate scale or re-take measurement) and an action in terms of generation of a variable measurement report.

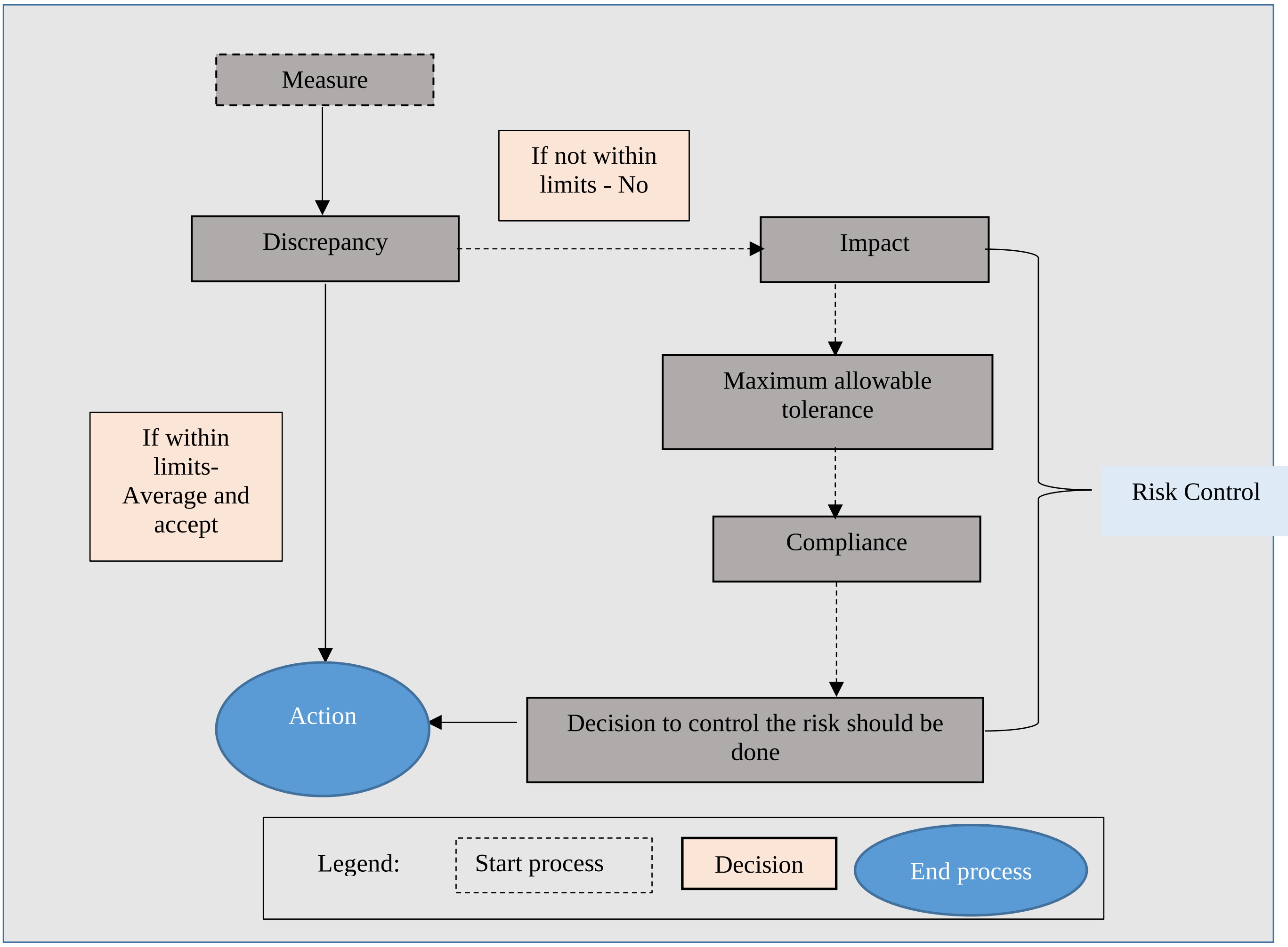


Figure 8.1 Framework for data verification and reconciliation
Source: Researcher's concept (2019)

The chapter also develops an intelligent reconciliation system in which the measurement of every variable should be captured with a defined sensor. Various technology options for data verification and analysis of variables were included as a contribution to new knowledge.

This chapter progresses with an implementation process for tracking metal content and other broken ore variables. This implementation process is developed for measurement, monitoring and tracking of volume and mass, sampling for the grade, fragmentation, density, moisture content as well as location-based information. The implementation process is made up of steps with unique colour conventions. This process includes identification of the purpose for the measurement, the technology/equipment used for that particular measurement, development of a site based specific protocol for each of the equipment and a competency standard. The chapter depends on discussions from previous chapters and annexes to demonstrate some concepts.

8.2 Intelligent Reconciliation system

Several systems have been developed for different purposes in the mine and metallurgical processes. These systems perform various mine and plant-based analyses. The plant historian system, for example, is a software that collects plant data from various plant equipment and laboratory information management systems (LIMS) and stores the data in a database for analyses. The data is further analysed based on control limits that are provided for in the software.

An example of an intelligent system that highlights various variables of interest and enables an intelligent reconciliation of measurement variables along specific critical measurement points is depicted in Figure 8.2. Production variables such as volume/mass/tonnage, grade, fragmentation, moisture content, and location-based information can be measured, monitored and tracked at every critical measurement point as depicted in Figure 7.2 of the previous chapter.

The workflow outlined in the reconciliation system is to measure the variable of interest; determine the discrepancy; determine risk; control the risk in order to assess the impact of the discrepancy; decide on tolerance or control limits; assessment of compliance to measurement protocols; action required depending on the outcome of the previous themes; and generation of a report on the specific measurement variable.

An improvement strategy would be required towards best practice.

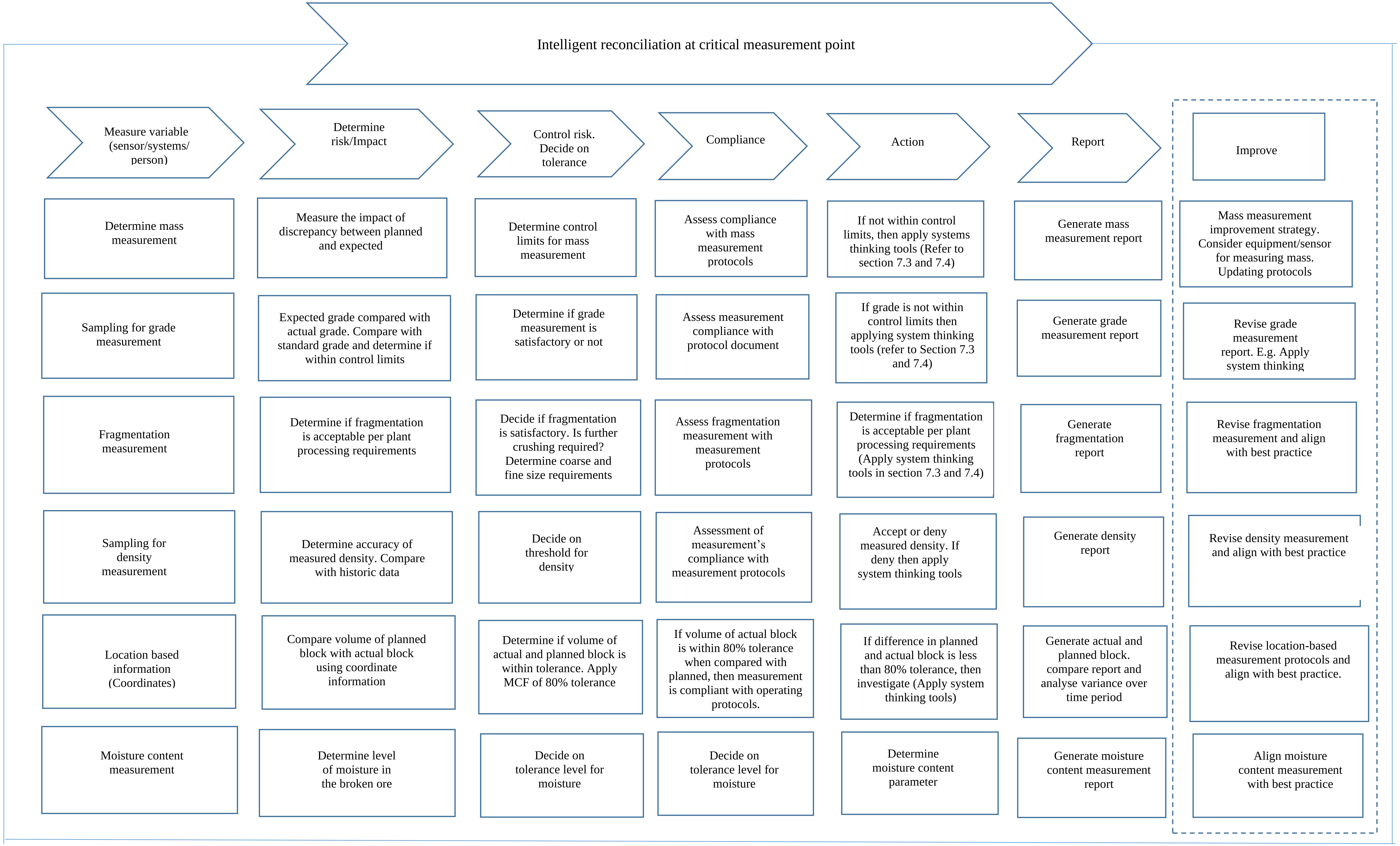


Figure 8.2 Intelligent reconciliation at critical measuring points (Source: Researcher's Concept, 2019)

8.3 System design for time and spatial tracking of ore from underground to the surface

The system for tracking ore from in-situ to plant entry includes the measurement, monitoring, modeling and data analysis of ore variables including volume/mass/tonnage, grade, fragmentation, density, moisture content, and location-based information. Real-time communication of these variables can be done to the control room on an integrated systems platform.

The conceptual framework for measurement, tracking, monitoring and modeling of in-situ and broken ore variables to plant entry is depicted in Figure 8.3. The first phase includes the tracking of location-based information of broken ore using existing sensor-based technologies. The second phase is the monitoring of grade, volume/mass, fragmentation and density parameters using sensor-based technologies. The third phase is the ore flow modeling using appropriate visualization software (e.g. GIS).

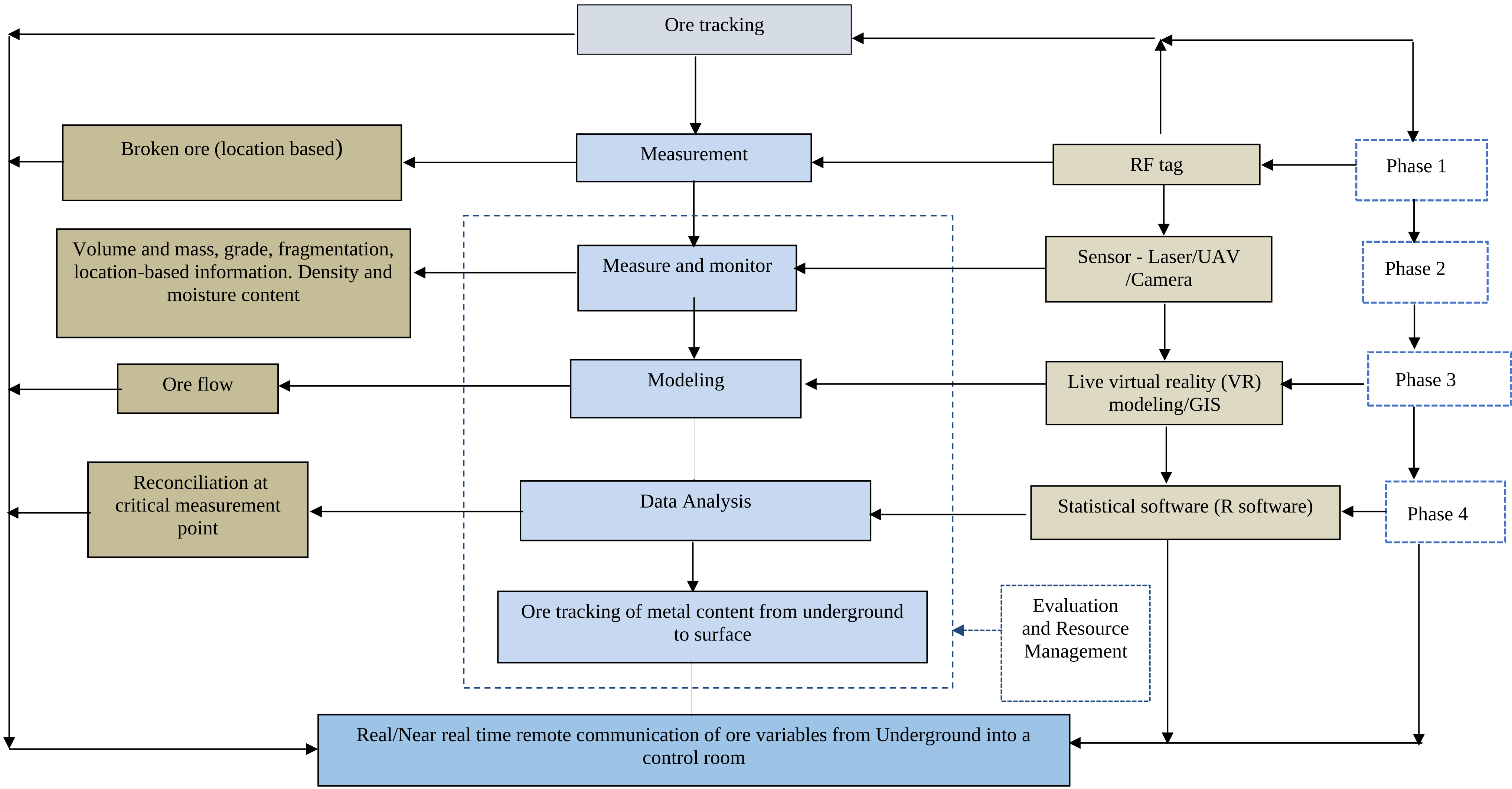


Figure 8.3 Conceptual framework for tracking broken ore from face to plant entry (Source: Researcher's concept, 2019)

The fourth phase is a mine-to-mill reconciliation analysis using historic data to identify trends and insights in the data. A particular area of interest is to identify high success areas in the flow stream as well as areas that may require improvement in terms of operating practices.

8.4 Measurement and monitoring at critical measurement points

Table 8.1 outlines the measurement and monitoring of in-situ and broken ore variables at specific critical measurement points referred to as stages A to E. The in-situ stage (based on resource model) referred as stage A. The second stage B is the after-blast stage, stage C is ore transportation, stage D is the point of tipping ore into bins and orepass, and the final stage E is the point of stockpiling ore on surface/plant entry. Samples should be taken throughout the stages (A to E), where possible to enable the measurement of grade, mass, fragmentation and location-based information to be measured, monitored and tracked.

Table 8.1 Measurement and monitoring of variables from in-situ to surface

A (In-situ based on block model).	B (After blast).	C (Ore transportation).	D (tipping into ore bins and orepass).	E (Stockpiling on surface and plant entry).
Grade Area/Volume Density Location	Grade Volume/ Tonnage Fragmentation Density Location	Grade Tonnage Fragmentation Density Location	Grade Tonnage Fragmentation Density Location	Grade Tonnage Fragmentation Density Location Moisture content

Source: Researcher's Concept (2019)

8.5 Technology options for tracking broken ore variables

Technology options for measurement of these variables at each critical measurement point/stage of tracking are outlined in Table 8.2 in terms of the activity at each stage, the measurement and monitoring variables, potential technology to be tested and the measured data expected.

At stage A (in-situ measurement), which is based on the resource model and or block model, the variables to be monitored are grade, area/volume, density, and location-based information.

Stage B involves the measurement and monitoring of after-blast material. Possible technologies for measuring volume/tonnage are laser scanner/UAV, and possible technologies for measuring fragmentation are UAV/video camera.

Stage C is when the ore is tipped into ore passes and bins. The monitoring variables of interest are grade, volume/tonnage, fragmentation, and density of ore that is tipped into the ore pass and the bins. Similar technologies used at previous stages can be used here.

Table 8.2 technology options for tracking in-situ and broken ore

Stage	Activity	Monitoring variable	Potential technology	Measured data	Requirement
A	In-situ measurement (Based on block model)	Grade	Hyperspectral scanner/Assign a grade value to block	Grade for that particular block	Mine's standard operating procedure (SOP) for Area and volume measurement.
		Area/Volume	Scanner e.g. Laser/ UAV	Area/volume for that particular block	
		Density check	Assign density value to block	Density for that particular block	
		Coordinates (Location)	Robotic total station/ laser scanner	Coordinates (Location)	
B	Broken ore and ore transportation	Grade	Hyperspectral scanner/measure grade and assign value	Grade	Obtain ore samples at this stage and measure grade and fragmentation using hyperspectral scanner for grade and UAV/Camera system for fragmentation
		Volume to convert to mass and tonnage	Scanner e.g. Laser/Lidar, UAV	The tonnage of that material	
		Fragmentation	Camera system	Fragmentation of that material	
		Density check	Assign density value to broken material	Density	
		Coordinates (Location)	Robotic total station/laser scanner	location	
C		Grade	Hyperspectral scanner/Assign a grade value	Grade	

	Tipping into ore bins and orepass	Volume to convert to mass and tonnage	Scanner e.g. laser or Lidar, UAV	Tonnage of that material	Obtain ore samples at this stage and measure grade and fragmentation using hyperspectral scanner for grade and UAV system for fragmentation
		Fragmentation	Camera system/Assign fragmentation value	Fragmentation	
		Density check	Assign density value broken material	Density	
		Coordinates (Location)	Robotic total station/laser scanner	Location	

D	Surface/Rom pad (Stockpile measurements	Grade	Hyperspectral Scanner/Assign a grade value	Grade	Obtain ore samples at this stage and measure grade and fragmentation using hyperspectral scanner for grade and UAV/camera system for fragmentation
		Volume to convert to mass and tonnage	Scanner e.g. laser /UAV	Tonnage	
		Fragmentation	Camera system/Assign fragmentation value	Fragmentation	
		Density check	Assign density value to broken material	Density	
		Coordinates (Location)	Robotic total station/ laser scanner	Location	
E	Plant entry	Grade	Hyperspectral Scanner/Assign a grade value	Grade	Obtain ore samples at this stage and measure grade and fragmentation using hyperspectral scanner for grade and UAV system for fragmentation.
		Volume to convert to mass and tonnage	Scanner e.g. laser or Lidar, UAV	Tonnage	
		Fragmentation	Camera system/Assign fragmentation value	Fragmentation	
		Density check		Density	
		Coordinates (Location)	Robotic total station/ laser scanner	Location	
				Moisture content	Refer to section 2.4.4

Source: Researcher’s conceptualization (2020)

At stage D (representing ore on surface/rompad), the monitoring variables of interest are grade, volume/tonage, fragmentation, density, and location-based information. Potential technologies for monitoring these variables are highlighted in Table 8.2.

Stage E is the point of tipping into the plant. The same technology options for measurement and monitoring in previous stages can be used to measure, monitor and track variables as outlined in Table 8.2.

8.6 Modeling and data analysis

The third phase from Figure 8.3 is ore flow modeling which would enable the spatial analysis of variances of quantities and qualities to be determined on a screen at a glance. Figure 8.4 illustrates the development of an information system for comparing planned mining areas with actual mining areas. Data analysis involves the use of an appropriate statistical technique to identify trends and insights in the mine to mill reconciliation data and can be visualized in a suitable visualization software such as GIS. Reconciliation between actual and planned quality and quantity estimates are traditionally determined using spreadsheets, however, this exercise would enable the variances to be spatially linked.

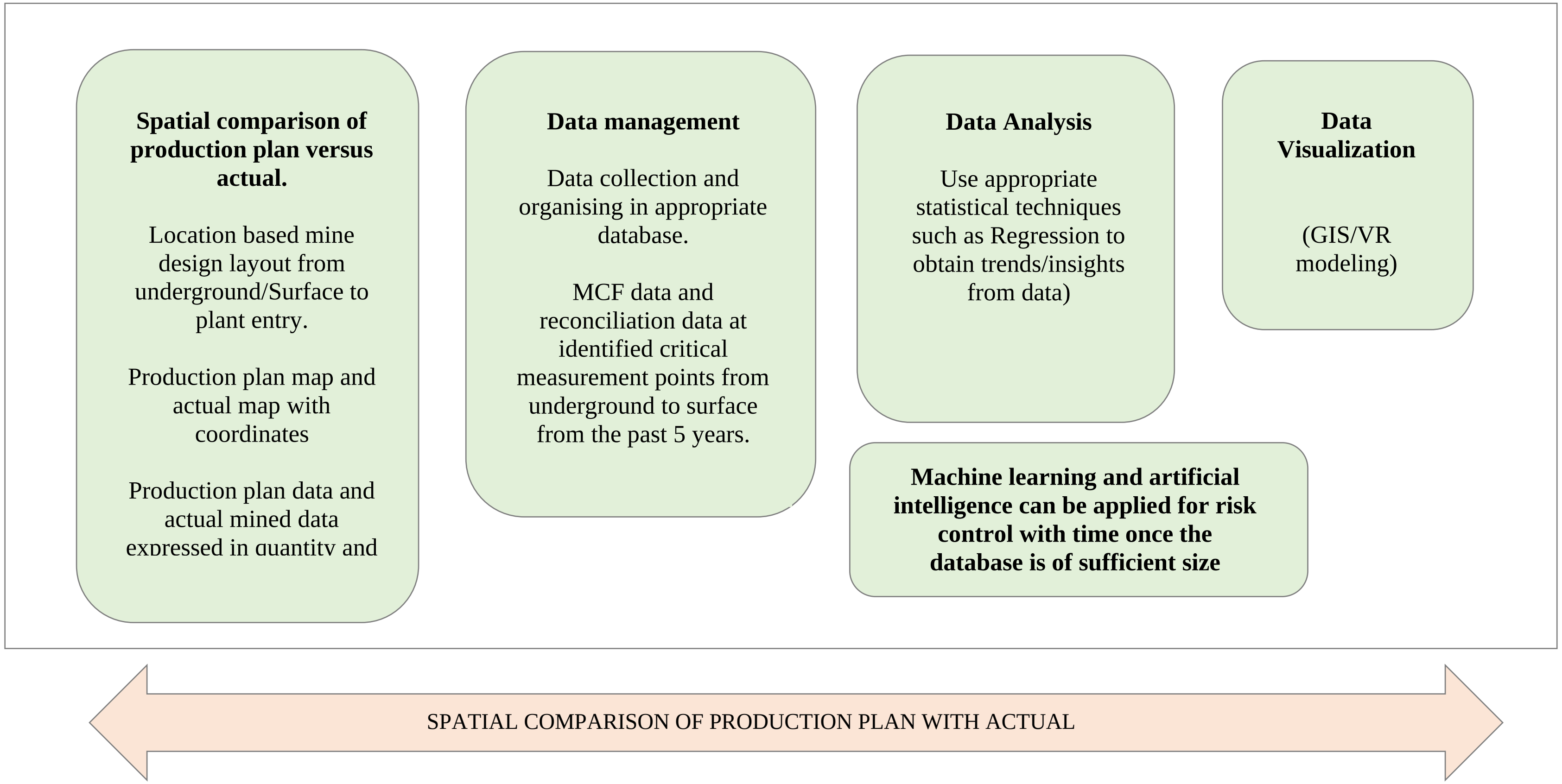


Figure 8.4 Spatial comparison of planned and actual quality and quantity estimates in GIS (Source: Researcher's conceptualization, 2020)

8.7 Implementation process for ore tracking

The section develops an implementation plan for tracking metal content and ore variables discussed previously. An implementation plan is developed for measurement, monitoring and tracking of volume/tonnage, sampling for the grade, fragmentation, density, moisture content as well as location-based information. This implementation process is made up of several steps with unique colour conventions illustrated in Figure 8.5. This includes identification of the purpose for the measurement, the technology/equipment used for that particular measurement, development of a site-based specific protocol for each of the equipment and a competency standard. Some concepts were demonstrated using discussions from previous chapters and annexes.

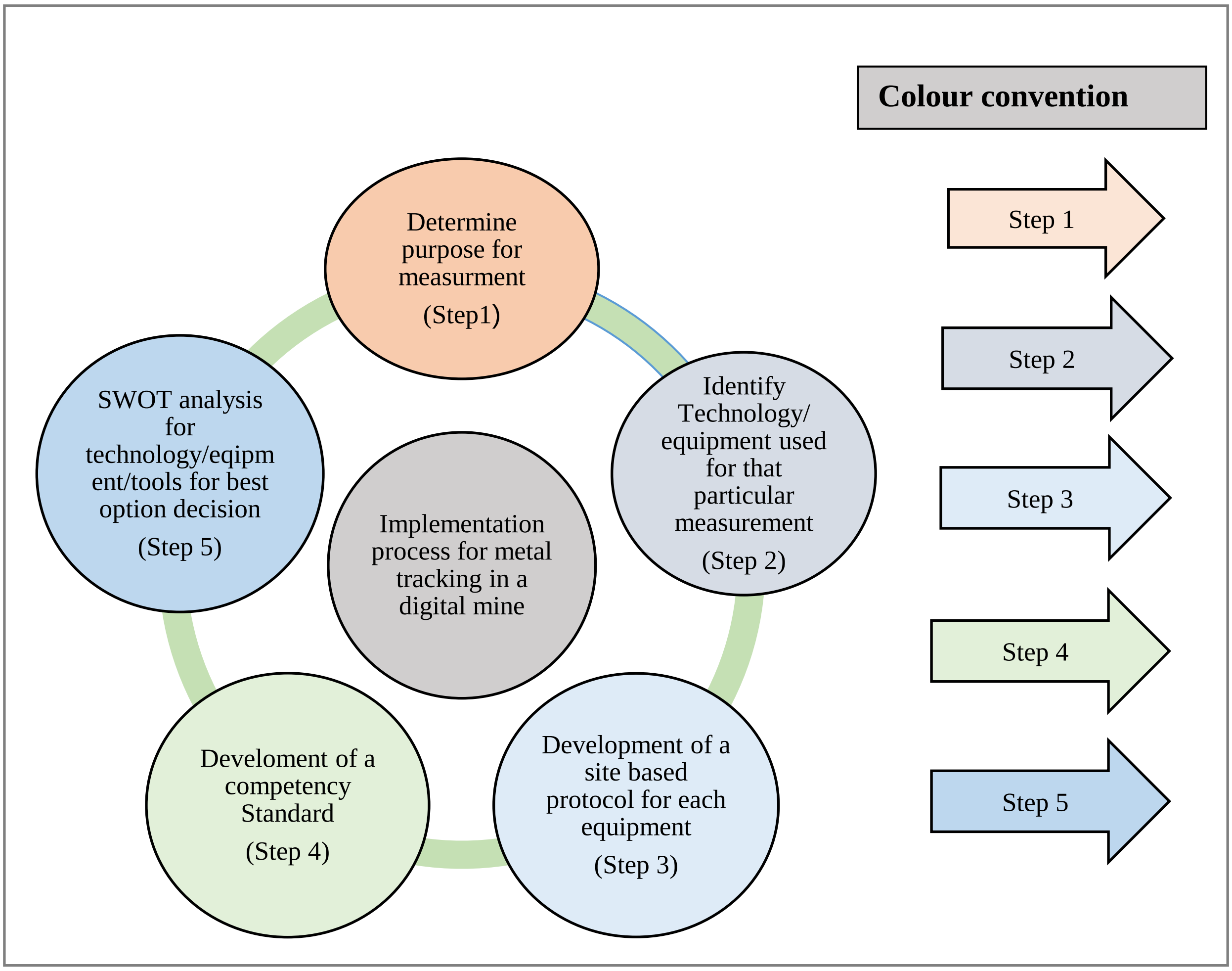


Figure 8.5 Implementation process for tracking metal content

(Source: Researcher's concept, 2019)

8.7.1 Implementation plan for mass and tonnage measurement, monitoring and tracking

Figure 8.6 shows the implementation process for conducting a mass/tonnage measurement for the purpose of ore and metal accounting from underground to surface. The first step is to identify the purpose of the measurement; the second is to decide on the equipment for the mass measurement; the third step is to develop a standard operating protocol which is site-specific; and the fourth step is to develop a competency standard for each technology/equipment used and identified as a potential for mass measurement.

The purpose of mass measurement can be classified in terms of mass measurement for production and plant purposes. Mass measurement for production purpose includes face advance measurements, relative density determination, stocks and inventory measurements (stockpile measurements, the mass of ore in bins, mass measurement required for custody transfer, mass measurement required for secondary metal accounting, mass measurement required for plant control monitoring).

For the various classification of mass measurement for plant purpose, refer to (JKMRC 2008:78):

- Measurements required for custody transfer and primary metal accounting[36];
- Measurements for secondary metal accounting[37];
- Mass measurement required for plant control monitoring[38].

The tonnage of ore can be determined given the density of the broken ore and the volume of broken material.

[36] E.g. is measurement for input and output streams to plant operation. A high-quality standard measurement is required.

[37] This measurement is for management control and includes internal company transfers and plant performance. It may also be used for cross checking primary accounting. Measurement for environmental monitoring also falls in this area.

[38] All mass measurement for plant control monitoring purposes.

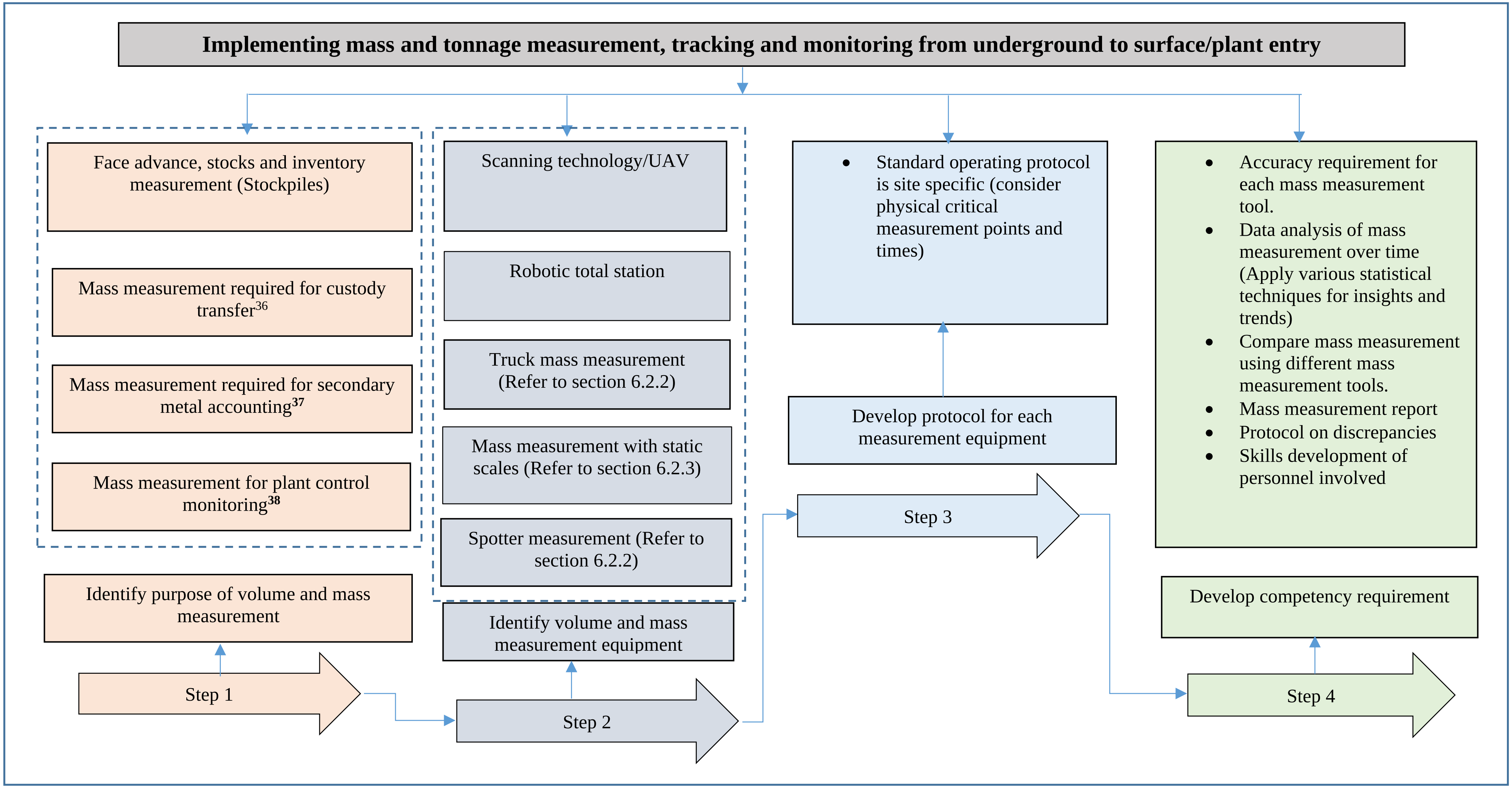


Figure 8.6 Implementation plan for mass and tonnage measurement, monitoring and tracking
Source: Researcher's concept (2019)

The second step is to decide on the mass measurement equipment. The purpose of the measurement should inform the choice of technology or equipment. Technology options for mass measurement from underground to surface are highlighted in Table 8.2. For practical purposes, area/volume/mass measurement can be conducted using scanning equipment, and traditional techniques such as truck mass measurements and mass measurements with static scales as was discussed in chapter 6 (section 6.2.2). The development of a standard operating protocol (step 3) is site-specific and should be done for all the mass measurement equipment identified from underground to surface and plant. Considerations should be made for the critical measurement points and times of measurements as captured in a typical underground mechanised mine ore movement in Figure 7.2 (chapter 7).

Step 4 includes the development of a competency standard for mass measurement. Issues such as accuracy should be considered (Refer to chapter 2 section 2.4.9 and chapter 6, section 6.2.1). Statistical techniques for analysing measurements from different sources should be considered. Issues of discrepancy should be accounted for. This requires skills development for the personnel involved in the mass and tonnage measurement. For example, the actual tonnage measured and tonnage obtained from the resource models (referred to as planned measurement) can be analysed using various statistical techniques. For the purpose of demonstration, various statistical techniques can be used to analyse actual tonnage measurements and planned tonnage measurements at a typical underground mine over a specified period (Refer to Annexes A5, A6, A7, A8 and A9).

8.7.2 Implementation process for sampling and grade measurement monitoring and tracking.

The implementation process for tracking metal content from underground to surface is displayed in Figure 8.7. The first step in this process is the determination of the purpose of sampling (face sampling, plant/metallurgical, exploration, laboratory sampling of precious or base metals and bulk commodities, sampling of slams and tailings dumps). The second step is to identify the class of sampling. The classes of sample are classified in terms of the type of samples obtained and the locations from where these samples are obtained. The third step is to identify an appropriate sampling tool/equipment. For a digital mining approach, the preferred option is to use a sensor-based technology such as the grade analyser for sampling purpose. However, a combination of digital sampling and manual sampling would be useful for monitoring accuracy and checking reliability of results. The fourth step in the process is to develop a standard operating protocol for every sampling tool that is used at the mine and should be subject to renewal and approval by management. The 5th step in the process is to build a competency standard for sampling personnel. Such a standard should take into consideration issues of accuracy requirements (refer to chapter 2 section 2.4.9 of this thesis). A well-defined QAQC procedure and method should also be included in the competency standard. Part of the procedures to work towards best practice is to develop a GIS for spatial comparison of planned grade versus actual grade obtained from mining (Refer to figure 8.4 in chapter 8). Grade variance maps can be used to measure, monitor and track grade variables from different sources such as planned grade, best cut grade and actual grade (in the case of a typical underground mechanised mine) to enable an improvement in defining the ore body. This is best done using the block model. Refer to Annex A10 for an example using actual grade from a mined-out area in comparison with planned grade and best cut grade.

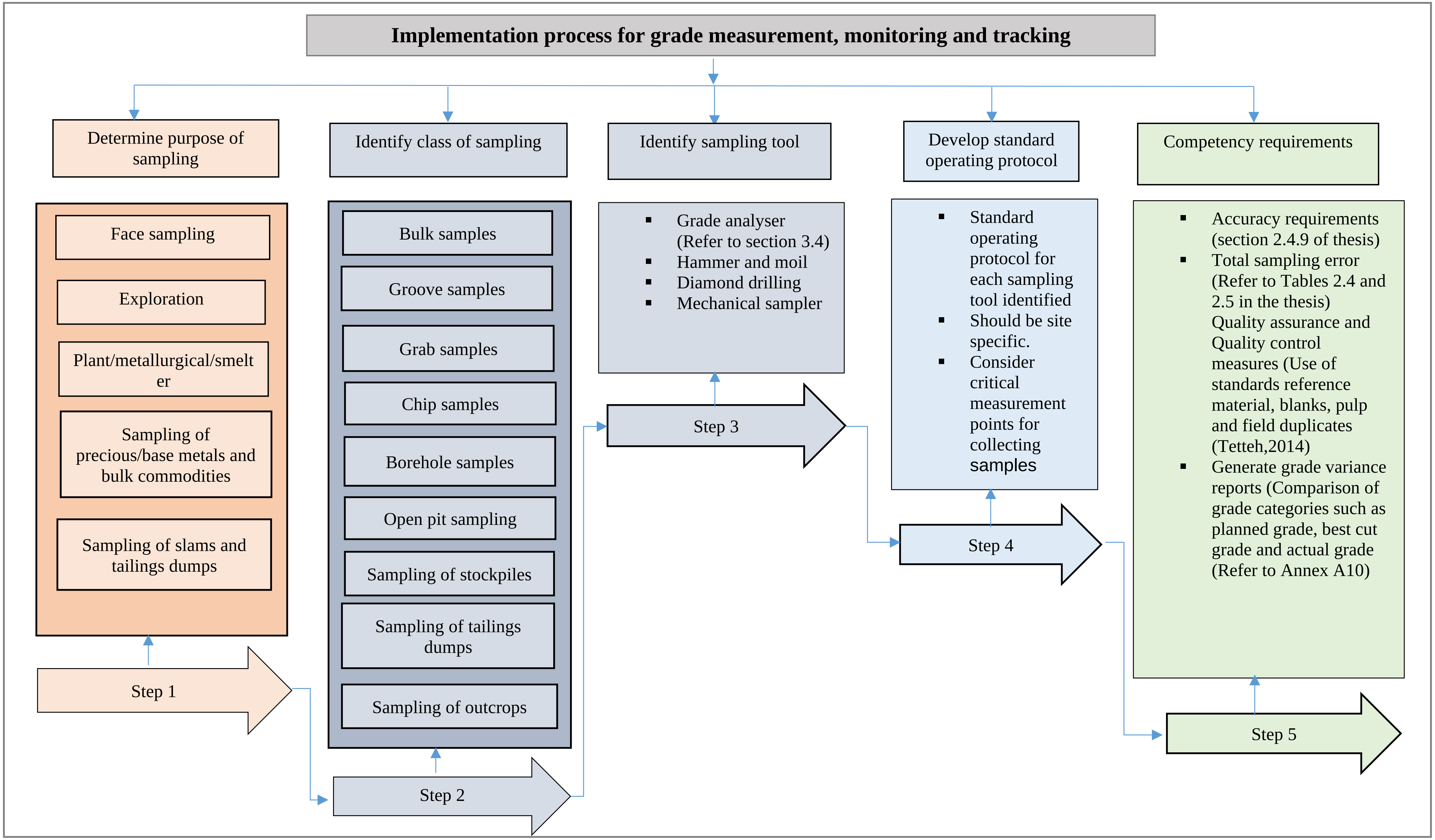


Figure 8.7 Implementation plan for tracking grade
(Source: Researcher's Conceptualization, 2019)

The Standard operating protocol for sampling should cover all the equipment/tools used for sampling. It is important to recognise that this is also site-specific. The competency standard should cover accuracy requirements (Refer to chapter 2 sections 2.4.9 of thesis). Tables 2.4 and 2.5 in chapter 2 also explains the Total sampling errors, which should be captured in the grade analysis reports. QAQC measures should also be part of the competency standard [Refer to (Tetteh,2014) for QAQC analysis procedures].

8.7.3 The implementation process for fragmentation measurement monitoring and tracking

The implementation process for measuring, monitoring and tracking fragmentation from underground to surface consists of a five-step process (Figure 8.8). The initial step is to identify the purpose of fragmentation. The second step is to decide on fragmentation measurement points in the upstream process. Several considerations in terms of critical measurement point to measure, monitor and track fragmentation should be made in this step as this would enable a successful mine to mill optimization process to be achieved. Fragmentation measurement points could be underground (after blast images), an online camera system which is fixed on the conveyer belt to measure fragmentation at every tipping point, and finally fragmentation measurement of rock in the load-haul-dump bucket. Technology options for measuring fragmentation are outlined in chapter 3 section 3.3 and Table 8.2. Some of these sensors include the use of digital photogrammetry, 3D laser scanners, video camera technology and UAV technology (Refer to section 3.3 of the third chapter).

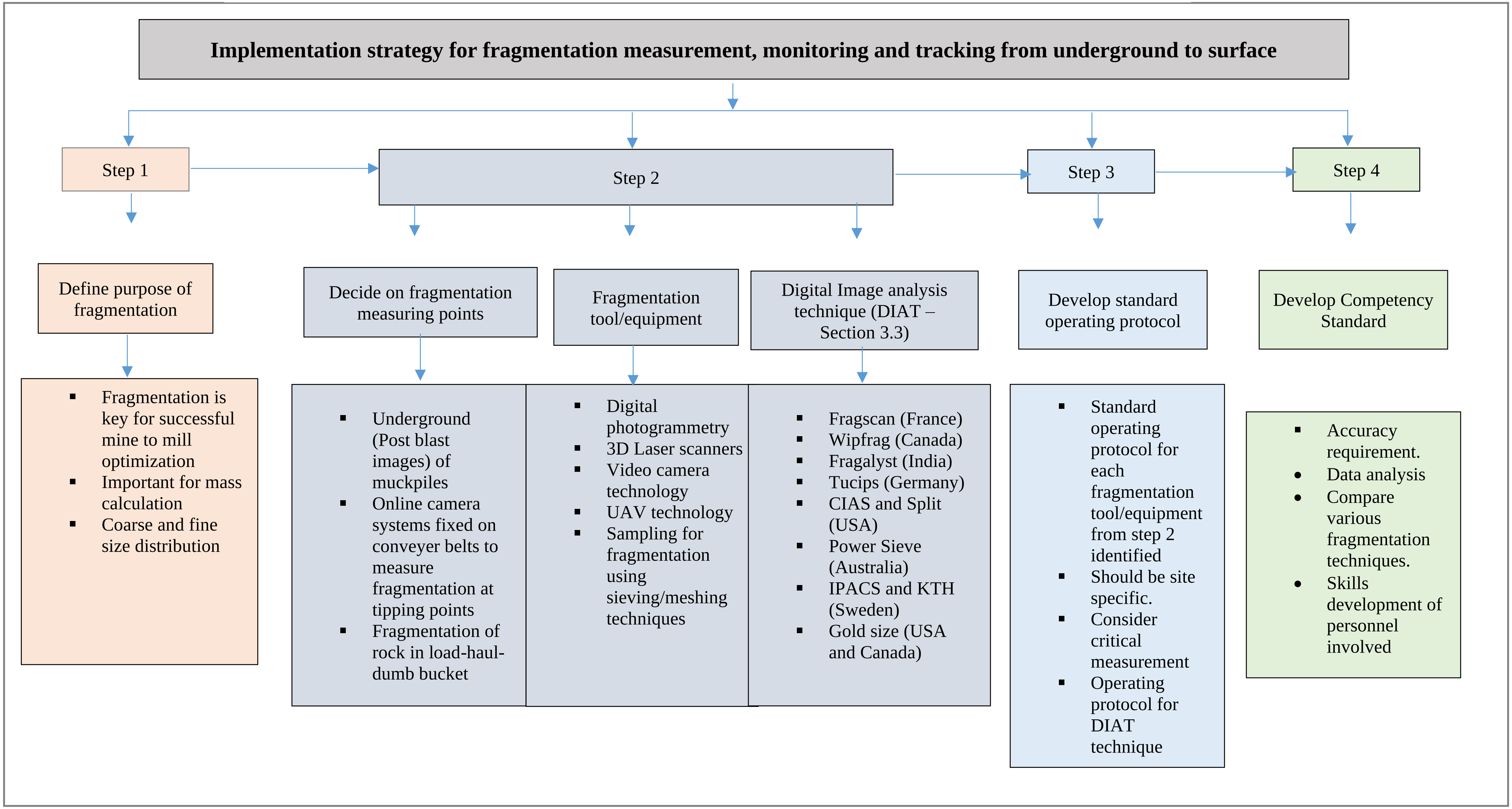


Figure 8.8 Implementation process for measuring, monitoring and tracking fragmentation

Source: Researcher's concept adapted from multiple sources: (Chakraborty et al, 2002; Raina, 2013; Cunningham 1996; Carlsson and Nyberg, 1983; Noy, 2006; Anderson et al, 2007; Thurley, 2009; Thurley, 2011; Sikmus and Dance, 2009; Brink *et al* 2008; Bamford et al, 2016)

The would be a need to monitor the accuracy of fragmentation by comparing results of the DIAT measurement with those obtained from sampling and sieving analysis. Steps 4 and 5 are concerned with developing standard operating protocols for each of the fragmentation equipment/tools and developing competency standards regarding accuracy measurements, data analysis and skills development of personnel responsible.

8.7.4 The implementation process for density and moisture content measurement, monitoring and tracking

The implementation process for density and moisture content measurement, monitoring and tracking consists of a four (4) step process (Figure 9.5). The first step is to define the categories of density measurement and moisture content. From Figure 9.5, it can be deduced that the density measurement is based on the physical characteristics of the ore body and practical conditions of the specific site. Moisture content is usually determined from a laboratory setting and later under defined conditions in an oven over a specific period of time to obtain the dry mass and subsequently the moisture content (Refer to section 2.4.4 of thesis for moisture content measurement and Archimedes method of density calculation for moisture content as an example).

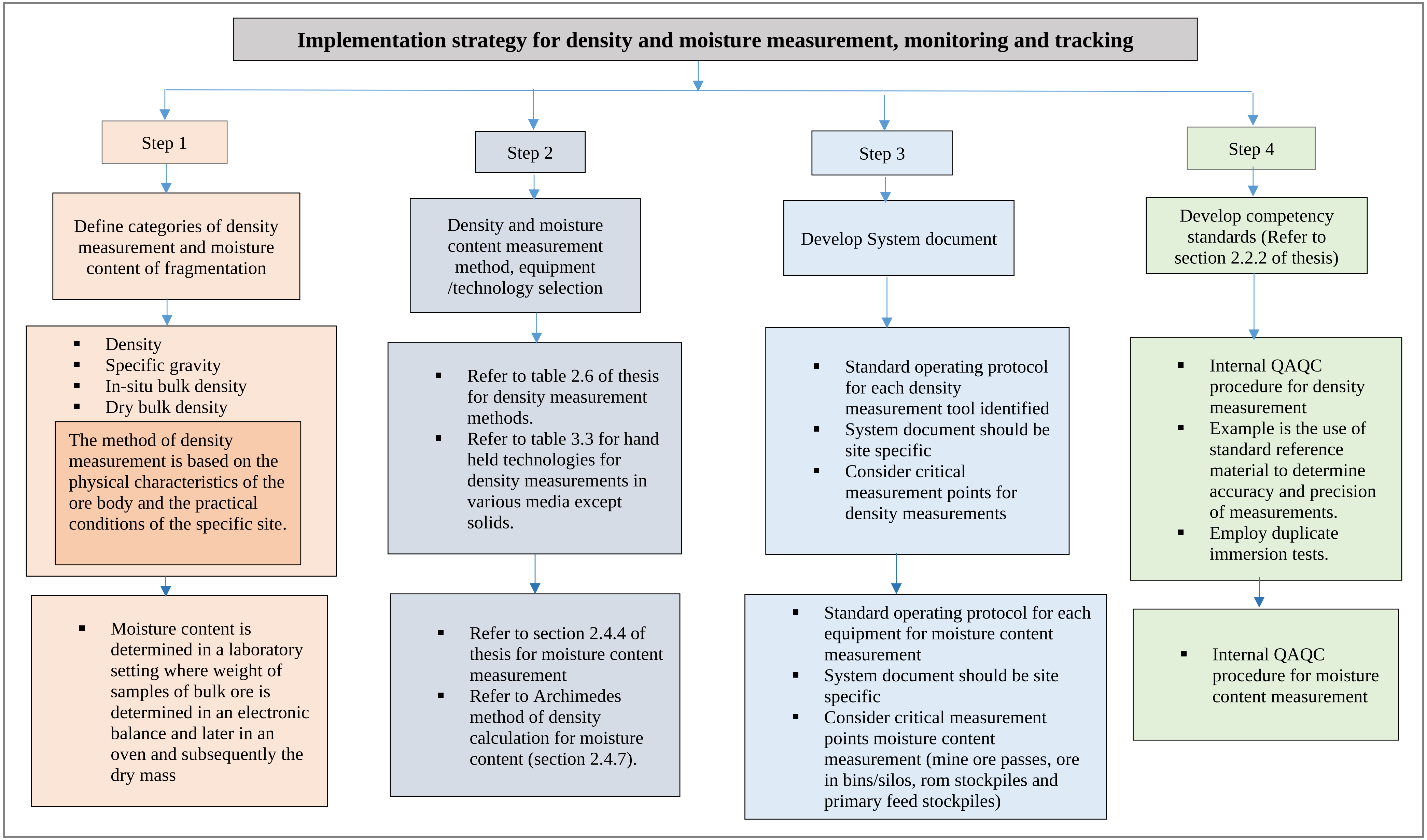


Figure 8.9 Implementation process for density and moisture content measurement, monitoring and tracking from underground to surface Source: Researcher's conceptualization, 2019)

The second step in the process is to select an appropriate technology or equipment for density and moisture content measurement, monitoring and tracking. Step 3 is to develop a system document for every equipment/tool that is used to determine moisture content and density. The fourth step is to develop competency standards in terms of an internal QAQC document for density and moisture content measurement. A typical example is the use of standard reference materials to determine the accuracy and precision of measurements.

8.7.5 Implementation for location measurement, monitoring, and tracking

The implementation process for location-based measurements involves a 4-step process (Figure 9.6). As was discussed in chapter 3 section 3.2, an ideal material tracking technology would be real-time satellite tracking from underground to surface. Other technology options include the use of RFID for material tracking; scanning technology to obtain as-built information as close as possible to the reality; and aerial photogrammetry. The second step in the process is to identify the technology tools required for each tracking technology from step 1. This would entail the hardware and software required. For RF tracking, the RF tag and readers were discussed under section 3.2.1 in the thesis. Scanning technologies were also discussed under section 3.2.2 in this thesis. UAV technology was discussed under section 3.3.2. Step 3 is to develop a standard operating protocol for every tracking technology/tool from step1 and 2. The final step 4 is to develop a competency requirement/standard for operating these technologies.

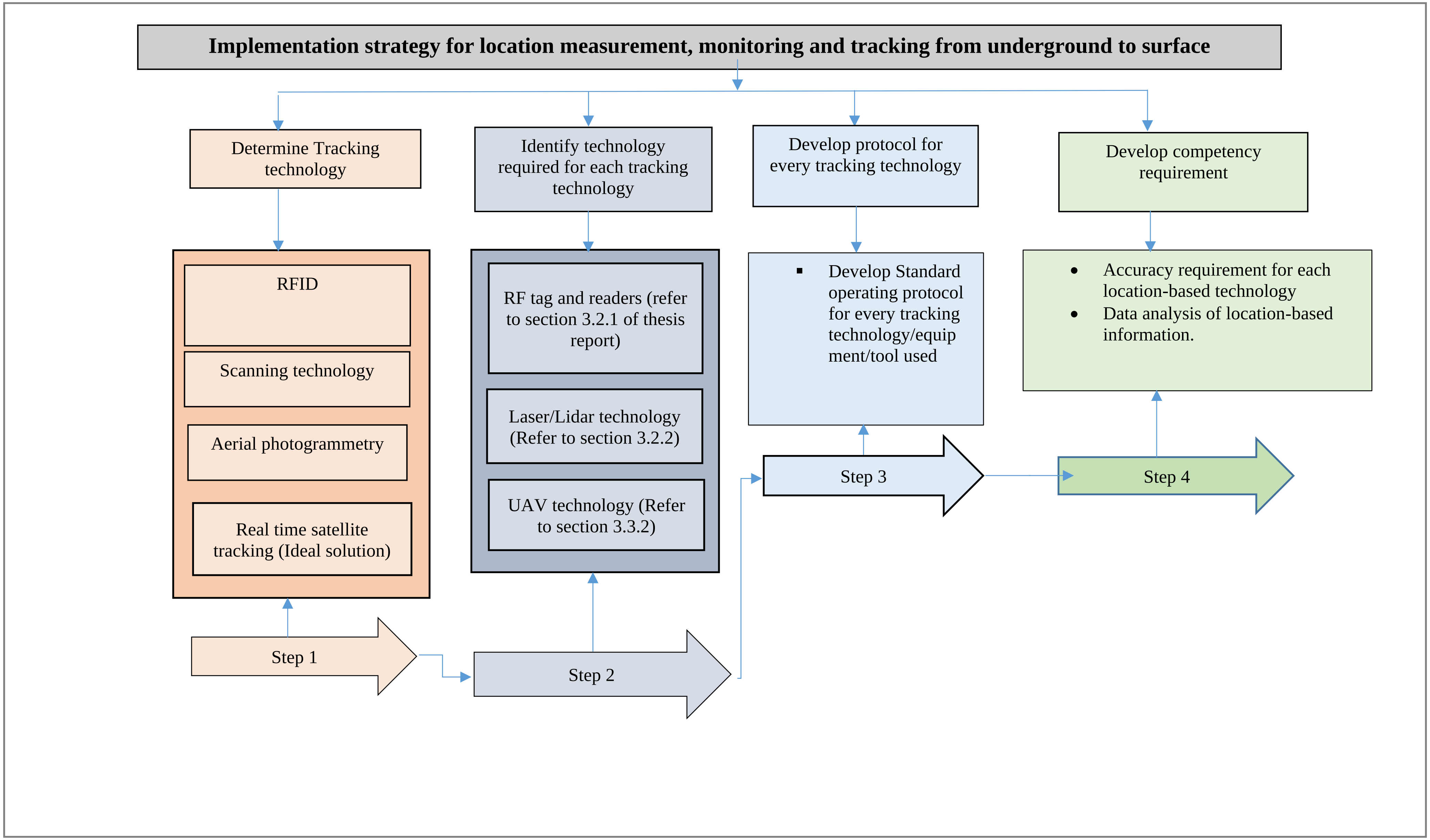


Figure 8.10 Implementation process for location measurement, monitoring and tracking from underground to surface (Source: Researcher's conceptualization, 2019)

8.8 Conclusion

This chapter summarised the conceptual framework for the time and spatial tracking of metal content from underground to surface as part of a solution to addressing the limitations in the data verification and reconciliation. Critical measurement points were defined as the in-situ stage referred as stage A; the after-blast stage referred as stage B; ore transportation referred as stage C; stage D is the point of tipping ore into bins and orepass; and the final stage E is the point of stockpiling ore on surface/plant entry.

In designing a system for reliable metal accounting for underground mines, an intelligent reconciliation system at each critical measurement point must be established. The processes outlined in the reconciliation system are to measure the variable of interest; determine the discrepancy between the planned and actual measurement; determine the level of impact of the discrepancy for risk control purpose; decide on tolerance limits; and an assessment of compliance to measurement protocols. A decision has to be made in terms of the measurement's acceptance or rejection. The system must also generate a report on each measurement variable. An improvement strategy is recommended towards best practice.

The chapter further developed an implementation plan for measuring, monitoring and tracking ore variables including volume/mass/tonnage, metal content, fragmentation, density and moisture content, as well as location-based information. The implementation process consists of defining the purpose of the measurement variable; identification of the best technologies/tools/equipment to use; development of a standard operating protocol for technologies/tools/equipment which should be site-specific; and a competency standard for the use of technologies/tools/equipment identified. The implementation process also relied on discussions from previous chapters and annexes to demonstrate some of the concepts.

The next chapter gives an assessment of digital technologies discussed for all the measurement variables to enable the best choice of technologies/tools/equipment that are applicable for each measurement variable.

9 Assessment of the combined digital mining technology (CDMT) approach for ore tracking

9.1 Introduction

The previous chapter developed a conceptual framework for time and spatial tracking of metal content from in-situ to surface/plant entry as part of the solution in addressing limitations in data verification and reconciliation in the context of ore and metal accounting. This chapter assesses the strengths, weaknesses, opportunities, and threats in using digital technologies for tracking metal content and broken ore variables. The chapter further gives an outlook of a combined digital mining technology (CDMT) approach. Such an outlook is meant to affirmatively answer the initial research question "Are combined digital technologies suitable for tracking, measuring and monitoring metal content from the mining face to plant entry?"

9.2 SWOT analysis of technology options for tracking metal

Ore and metal accounting start with the accurate measurement of mining excavations of volume/mass/tonnage, grade/metal content, fragmentation, moisture content and density. Currently total stations are used for volume measurements. Although total stations are accurate, some of the disadvantages are that it is time consuming, measures single points, and requires more than one person to work with. Laser scanners on the other hand give far more accurate volume measurements as well as detailed features in terms of support features, obstacles, quality of sweepings etc. From Table 9.1, the technology options for volume measurements are scanning technologies and traditional total stations. Scanning technologies are preferred technology options for volume measurements because they are fast and reliable. In addition to generating many points, they do not require targets (if they are georeferenced from a base station), making remote surveying possible by one person. Traditional total stations are still relevant for accurate positional surveys until such a time when the scanning technologies can do accurate positional surveys.

An objective in metal accounting is to balance the measured grade with the estimated one, hence the measured grade must be accurate. Although a grade analyser is presently not available, such a digital tool would enhance the process of grade measurements. This would serve as an enabler in eliminating human inherent errors which are associated with obtaining representative samples for further analysis in a laboratory.

The accurate measurement of fragmentation is key in achieving a successful mine to mill optimization process. Accurate fragmentation is also requirement for an increase in mine productivity and accurate mass calculation. The fragmentation parameter also affects the density for converting volume into mass. From the SWOT analysis in Table 9.1, it is seen that DIAT systems remain a significant and cost-effective tool for measuring and monitoring fragmentation in a real mining environment. However, because of issues such as obtaining a representative sample, there is a need to conduct digital measurements alongside the traditional sieving method of fragmentation to ensure measurements are accurate and reliable. A specific example is made to the study conducted by Sanchidrian et al, (2009) who realised that the image analysis method of fragmentation resulted in an error of not more than 30% of the coarse region of the rock sample size distribution and an error of 85%-100% in the fine region of the same distribution.

Table 9.1 SWOT analysis of technology options for combined digital mining technology approach

STRENGTHS	WEAKNESSES
Volume	
• Scanning technologies are fast and reliable (Scanners can measure up to 50 000 points per second (Refer to section 3.2.2)). • Scanning technologies do not necessarily require targets to work with if connected to a base station which makes remote surveying possible by one person. • Scanning technologies give detailed as-built measurement of features • UAV's makes it possible to measure areas that are difficult to access (E.g. Flood areas, underground working areas (although there are legal limitations), and deformation monitoring.	• Scanning technologies cannot be used for accurate positional surveys, which makes total stations still relevant. • Laser scanners are far more expensive than total stations. • Traditional survey equipment can measure fewer data in a longer period. (For e.g. 500 points in 4 hours)
Grade	
• Sensor-based technologies for grade measurements would be fast and reliable. • If a gold analysing tool is available for sampling, then issues with obtaining a representative sample would be resolved as the tool would enable measurements up to a defined depth. • Sampling results would likely be reliable since results would be less human dependent and therefore all human errors would be eliminated from the results as compared with the manual form of sampling.	• Sensor-based grade analyser developed by the former COMRO had issues with the accuracy of grade measurements. • Manual methods of obtaining samples and results are human dependent and therefore has inherent human errors which may not be easy to control or manage

Fragmentation	
• UAV systems are able to collect and analyse fragmentation data rapidly and in real-time. • The system helps in the reduction of cost and provides high-resolution images. • The use of DIAT systems keeps the operator away from harm or danger in a real mining environment.	• Accuracy issues: A study conducted by Sanchidrian et al, (2009) realised that the image analysis method of fragmentation resulted in an error of not more than 30% of the coarse region of the rock sample size distribution and an error of 85%-100% in the fine region of the same distribution. • Lighting systems underground may not be favourable to produce quality images.
Location-based information	
• The use of RFID for asset tracking has been possible for proximity detection systems to alert miners of the presence of static and moving equipment in their vicinity. • RF trackers have also been employed for tracking the location of explosives for security purposes. • RF trackers have been employed for tracking ore and waste parcels to prevent cross tramming. • High definition sensor instruments (RADAR and LIDAR) technologies are fast, reliable and accurate surveying technologies for material tracking. • High definition sensor instruments have great potential to provide optimal and detailed spatial data. UAV's are useful for remote material measurement, monitoring, and tracking.	• A real-time satellite tracking of material is non-existent. • High definition sensor instruments cannot be used for positional surveys like traditional total stations. • RF trackers can be linked to the material location but not give the exact location of the material. • UAV's cannot be used for positional surveys. • The microdot aerosol system propellant is flammable and not suitable for underground working areas especially in coal environments. • The visibility of the microdot code is affected by dust. • Microdots do not transmit signals to a reader and hence detection of microdot is done manually and not automatically.

OPPORTUNITIES	THREATS
Volume and Mass	
• Laser scanners have great potential to provide a detailed spatial representation of features. • Requires specialised skills for processing and analysing data. • To develop scanning technologies to conduct positional surveys.	• Since scanners can be operated by one person, issues of job losses become a concern as traditional survey methods require more than one person to operate • Several scanning technologies are available on the market which makes it difficult to choose from a lot. • Scanning equipment is usually costly.
Grade	
• Further opportunities to develop the grade analyser so that it can measure accurate grade values with acceptable limits of detection. • To further develop such a grade analyser tool such that it would be able to scan deeper into surfaces (1-5m) and possibly beyond 30m from the rock face. • An opportunity for mineral resource management personnel to obtain various software skills and data analysis that may be required.	• Fewer personnel may be required for obtaining and processing sampling data and results and therefore would lead to further job losses.

Fragmentation	
• To address the issue of fines correction, the software has been developed to apply a fine correction through sieve analysis and calibration. • The need to conduct further study on how to include the UAV system into a real mining environment to gain knowledge on its ability to be incorporated into the mine to mill optimization process, its value as well as accuracy requirements. • Ensure good lighting systems are installed underground to capture high-quality images.	• Challenges in terms of obtaining a representative sample size in terms of the number of images that are required for analysis. • The quality of images analysed in terms of high resolution. Software used for analysis usually does not have the capability to handle such high resolutions). • Scaling errors which occur when images get tilted. • Poor edge detection of images. • Errors due to bias from fine particles. This is because the size of fines are usually less than the size a DIAT system can detect.
Location information	
• Although satellite remote tracking from underground is currently not available, this is an opportunity for further research to enable specific ore types to be linked to their sources. • Opportunity to develop high definition scanners to perform accurate positional surveys. • Opportunity to develop UAV's to perform accurate positional surveys. • How to combine the Microdot technology in the ore flow process stream which is usually a complex one; • How to use the microdot technology to ensure easy identification of ore from different sources; • How to use the microdot technology to prevent misrouting challenges;	• High definition scanners are far more expensive than total stations. • Due to the flammable nature of the propellant in the microdot aerosol system, it cannot be used in the coal industry; • Due to the presence of dust in mine, it will be difficult to identify the codes of microdots. • The hardware components for satellite technology tracking may be huge and this might require a lot more hardware infrastructure and likely to be costly.

• How to use technology to minimize risks and identify potential hazards in real-time. • Real-time satellite tracking of material is an ideal solution that would enable satellite remote physical tracking of material flow (this technology would enable ore from various sources from underground to be linked to back to their original source/face. • Microdots still have the potential for tracking the location of ore parcels. This can be achieved if the microdots can be electronically detected	

Source: Researcher's conceptualization based on Multiple sources: Volume and Mass (Van der Merwe and Andersen, 2013); Grade (Klein et al, 2011; Hill and Garber, 1978; Davies, et al, 1979; Sims, 1980; Magri and Hawkins, 1987; Wills, 1992; Ketelhodt, 2009; Wotruba, 2006; Salter and Wyatt, 1991; Lerm, 1994; COMRO, 1990); Fragmentation (Cunningham 1996, Palangio, and Franklin, 1996; Sanchidrian et al, 2009)

An ideal solution for real-time tracking of material from underground throughout the value chain is satellite tracking. Although this option is currently not available, several tracking technologies are employed in the tracking of material attributes such as (location of ore parcels, fragmentation, density, content, moisture content, etc.) in the production process. From the SWOT analysis in Table 9.1, it can be deduced that the best technology option for material location measurement, monitoring and tracking is the real-time satellite tracking which is not existent as discussed previously. Such a technology would enable the location of physical ore parcels to be measured, monitored and tracked to the smallest detail. However, current location tracking technologies such as RFID, high definition sensors are still great for location measurement monitoring and tracking.

9.3 CDMT approach for tracking metal content from underground to surface

In order to answer the research question “are combined digital technologies suitable for tracking, measuring and monitoring metal content from the mining face to plant entry?’’ It was necessary to provide an outlook in-terms of its practicality in the context of ore and metal accounting. Figure 9.7 is the researcher’s conceptualization of a CDMT for tracking metal content and its associated variables from underground to surface. This consists of the various stages of tracking broken ore variables discussed in Table 8.1 of chapter 8. These stages include in-situ stage, after blast stage, during ore transportation, at ore tipping points such as bins/ore passes and stockpiling on surfaces. With specific reference to hard rock mining, at every stage of metal content tracking, a decision has to be made for which technologies or tools are applicable at each stage of the tracking (Refer to SWOT analysis for each of the technologies/tools discussed in section 9.7 of thesis for best solution). The action required at each stage of metal content tracking (specific ore and metal content variables) is to develop standard operating protocols and competency standards for the technologies or tools selected at the decision level.

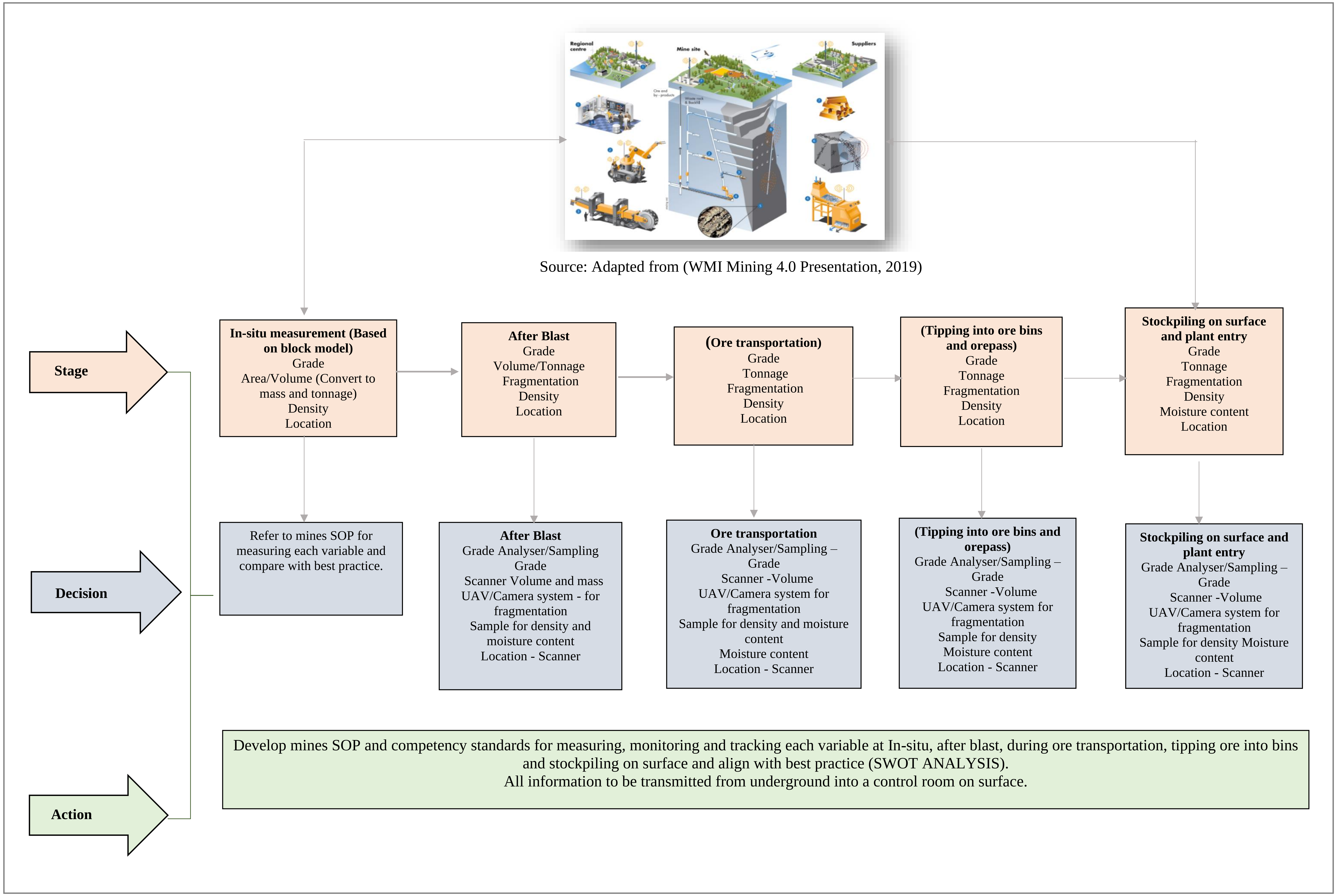


Figure 9.1 Combined digital mining technology approach for tracking metal content from underground to surface
(Source: Researcher's Conceptualization, 2019)

9.4 Conclusion

In this chapter, a SWOT analysis tool was used to determine the best technology options for the measurement of each of the variables. From the SWOT analysis in Table 9.1, it is seen that scanning technologies are preferable for volume measurements because they are fast and reliable. As compared with traditional total stations, they do not necessarily require targets to work with which makes remote surveying possible by one person. Traditional total stations are still relevant for accurate positional surveys until a time when the scanning technologies can do accurate positional surveys.

From the SWOT analysis in Table 9.1, it is again seen that the preferable option for metal content is the grade analyser. Although a grade analyser is presently not available, the existence of such a tool would enhance the process of grade measurements as well as aid in eliminating human inherent errors associated with obtaining representative samples for further analysis in a laboratory. The sampling method for grade measurement is however still appropriate.

Furthermore, the SWOT analysis diagram revealed that the DIAT systems remain a significant and cost-effective tool for measuring monitoring and tracking fragmentation in a real mining environment. However, because of the issues with accuracy discussed under the weaknesses and threat section of Table 9.1, there is a need to conduct digital measurements alongside the traditional sieving method of fragmentation to ensure measurements are accurate and reliable.

It was deduced that the density and moisture content measurement are based on the physical characteristics of the ore body and practical conditions of the specific site.

Moisture content is usually determined from a laboratory setting and later under defined conditions in an oven over a specific period of time to obtain the dry mass and subsequently the moisture content.

In the development of standard operating protocol for measurement, monitoring and tracking of ore variables, the site conditions should be taken into consideration. The use of a QAQC document to ensure the accuracy and reliability of the measurements should also be used. A typical example is the use of standard reference materials to determine the accuracy and precision of measurements.

From the SWOT analysis, it can be deduced that the best technology option for material location measurement, monitoring and tracking is the real-time satellite tracking which is not existent. Such a technology would enable the location of physical ore parcels to be measured, monitored and tracked to the smallest detail. However, current location tracking technologies such as RFID, high definition sensor technologies are still great for location measurement monitoring and tracking.

The chapter concludes with the researcher's conceptualization of a CDMT approach with specific reference to a hard rock mining environment (Figure 9.7). This consists of the various stages of tracking broken ore variables at the in-situ stage, after blast stage, during ore transportation, at ore tipping points such as bins/ore passes and stockpiling on surfaces. At every stage of metal content tracking a decision has to be made for which technologies or tools are applicable at each stage of the tracking (SWOT analysis discussed in this chapter is useful for best practice determination of technologies). In the researcher's conceptualization of a CDMT approach, an action is required in terms of the development of a standard operating protocol and competency standards for the technologies or tools selected at the decision level.

The next chapter is a summary of the thesis with general recommendations with regards to findings and highlights on areas for further research.

10 Conclusions, Recommendation and further research

10.1 Introduction

This chapter is a summary of the entire thesis with recommendations for future considerations and also for further research. The summary is given chapter by chapter in subsequent sections.

10.1.1 Chapter One: Introduction

The chapter outlined the research background with reference to digital technologies and their development in the mining space. The chapter also provided the context of the research, assumptions made, objectives, problem statement and structure of the thesis. The chapter further highlighted issues of operational uncertainties in the South African mining industry in which there was a decline in the production of some major precious metals such as Gold (Figure 1.4). This was further confirmed with the MCF of seven South African AngloGold Ashanti mines (Figure 1.5). The MCF in these mines averaged at 70% over a seven-year period. The loss in monetary value over this seven-year period was approximately 1.4 billion rand and total revenue obtained in this period was also about 3.4 billion rand. The issues of metal losses from the mining face to recovery were also captured as a major problem in mining companies which was not solving. An example is when actual measurements and planned quality, quantity and time estimates from various measurement systems do not reconcile. Although there are apparent and real physical losses that occur in this process, the aim in the thesis was to investigate digital technologies for measuring, monitoring and tracking metal content and broken ore variables (metal content, area/volume/tonnage, fragmentation, density, moisture content, and location-based information) from underground to surface. The chapter concluded with the development of a conceptual model for ore flow from the mining face to surface relative to the mine plan (Figure 1.9).

10.1.2 Chapter two: Mine call factor theory towards an implementation model for digital mine

The second chapter discussed the theory of MCF. This theory cuts across various technical disciplines, ranging from resource estimation, mine planning processes and reconciliation between actual and planned quality and quantity estimates. This includes the mining and processing stream, and the measurement of various broken ore variables (volume and mass, grade, fragmentation, density, moisture content).

A scientific approach for conducting MCF investigation was developed by Cawood (2003) by analysing some variable components from an underground perspective suggested by Storrar (1981), at the time. A finding of the MCF investigation conducted by De Jager (1997) in Western holdings mine also questioned the accuracy of grade estimation. Tetteh and Cawood (2014) developed the variable components of the MCF from a surface mine perspective.

Although a standard operating procedure for sampling practices has been documented by Minnitt (2010, 2013, and 2014) who described the various aspects of the total sampling errors based on Gy's sampling program, the researcher perceives that many mining companies preferred to develop their own procedures for sampling practices. This is necessary because sampling procedures are site-specific.

The chapter further identified the measurement of broken ore variables which influences the MCF. These are the volume/mass/tonnage, grade/metal content, density, moisture content, fragmentation measurements as well as ore dilution and ore loss determination procedures. The aim of every measurement, however, is to obtain an accurate measurement. The ability to effectively track and monitor these variables with georeferenced technologies throughout the production chain could lead to the possible determination of physical ore losses to enable proactive decisions and preventive measures to be made.

An implementation model for design considerations for digital mine is discussed. In this model, a single truth is established in a data warehouse in a control room where opportunities for generating reconciliation reports, communication of losses through an alert system and proactive decisions and analysis can be made. This chapter also proposes the possibility of applying big data analytics as a possible solution to the concepts of MCF issues.

10.1.3 Chapter three: Material monitoring and tracking technology options

The third chapter discussed digital technologies that have been used in the past for tracking and measurement of broken ore variables. These include tracking technologies such as RFID for ore tracking; scanning technologies for measuring volume, mass and location-based information; video camera and unmanned aerial vehicles for measuring and monitoring fragmentation; sensor-based technologies such as gold analysers for measuring metal content; and the microdot technology which was tested in the thesis as a viable technology solution for ore tracking. Although handheld technologies for density measurement are discussed in this chapter, the media type for use of these technologies does not include solids.

The chapter also discusses the concept of big data as data arriving from various systems, sensors, mobile devices and or multiple sources at startling volume, velocity, variety and variability. Various statistical techniques are used to analyse big data which are often represented in various visualization software (refer to Table 3.4).

10.1.4 Chapter four: Leading mine planning and reconciliation software options

The fourth chapter discussed various spreadsheet software that has been used over time. A list of spreadsheet software and their descriptions, file formats, compatibility with operating systems was outlined in Table 4.1. Although the commonest spreadsheet used in the mines is an excel spreadsheet, others that have been used in the past for both mining production and metallurgical accounting are the lotus 1-2-3 and Quattro Pro. The AMIRA code of practice, however, does not encourage the use of excel spreadsheets for metal accounting because of the likelihood of having the spreadsheet system modified by a metal accounting personnel to suit specific reporting needs. To remedy such a situation, the code advises the use of available commercial metal accounting software package.

The chapter further discussed Snowden's reconciliation software and its implementation at the Telfer mine in North-Western Australia. The system is web-based and allows read-only access to users, however administrative privileges such as editing can be granted. The reconcilor system provided the Telfer mine with the requisite tools to capture the accurate data, validate from all the relevant sources and therefore enabling a single set of numbers for ore tracking.

The Deswik software was also discussed in this chapter. Deswik has also developed several software suites for planning, geology and survey. The software solutions although not integrated into a single dashboard, can be used in various mining methods and also for various metal commodities.

Another leading practice software solution discussed is MineRP which has developed a spatial platform that integrates all mining technical data onto a central dashboard and therefore, the status of the mining activity can be viewed in 3D as a single picture. Other activities such as the mine design, scheduling, asset management can be done on this single dashboard.

10.1.5 Chapter five: Real-time material tracking: Testing the suitability of the Microdots technology for ore tracking

The fifth chapter highlights the test done in determining the suitability of Microdots in core and broken ore samples as a viable ore tracking solution. The experimentation work involved the basic measurements conducted on core samples obtained from the Anorthosite rock samples of the Bushveld igneous complex. Basic measurements of mass, volume and density were conducted on all the nine samples. The average density recorded is 2 795.569 kg/m^3 which falls within the density range defined by (Roelofse, 2010) of 2 730kg/m^3 and 2 800kgm^3.

The basic structure of Microdots was determined by cutting thin section cores and spraying with Microdots. Laboratory test was carried out to determine the visibility of Microdots on core and broken samples using 10 000, 5 000 and 3 000 Microdots systems. Samples were immersed in water for 24 hours and the results showed Microdots were still visible on all the samples when placed under the Carl Zeiss-Stemi 2000c microscope. Samples were placed in an oven and heated to a maximum of 100°C due to laboratory limitations. Samples were then allowed to cool down to room temperature. From results obtained, it was observed that heat had no effect on Microdots visibility on core samples since Microdots codes were still readable under the microscope. After stages one, two and three of the experimentation, it was realised that the data integrity of Microdots is not affected by water and heat. The final stage involved the crushing of samples into coarse and fine sizes. Crushing was done using Rocklab crushing machine. The coarse sizes range from 2cm to 3cm, and the fine sizes range from 3.35mm to less than 1mm. After crushing samples into coarse sizes, Microdots were visible with the naked eye and the codes were readable under a microscope. Coarse particles were then crushed into smaller ones (3.35mm-<1mm). Samples were further screened to classify them in sizes (>3.35mm, within 2mm and 3.35mm, within 1mm and 2mm, and less than 1mm). Checking Microdots visibility showed that Microdots are seen on particle sizes from 2mm upwards.

A SWOT analysis was undertaken to evaluate the Microdot technology as a viable tracking solution in relation to past and present tracking technologies in the mining industry. The analysis showed that although data integrity was retained after subjection to heat, water and crushing, the threats of the propellant of the aerosol system being flammable makes it a bad choice in for e.g. the coal industry which faces frequent spontaneous combustion issues. Additionally, the technology would not be suitable in an underground mine due to ventilation issues. Microdot technology would therefore not be considered as an option in the implementation strategy for the development of real-time material tracking, discussed in chapter 9.

10.1.6 Chapter Six: Real-time material tracking: Volume and in-process inventory measurement towards real-time material tracking

Chapter Six highlights the theory of in-process metal inventory measurement methods. Three methods namely the Direct, Indirect and Redundant methods were discussed. The direct method requires an accurate measurement of the ore variables such as dry mass, metal assay, wet ore mass, moisture content, density, etc. to determine ore stockpile metal inventory. The challenge with the direct method is that each of the variables described previously comes with a potential accuracy issue. Whether it is mass measurements or sampling and assaying for content grades. The direct method needs a careful assessment of all the variables.

With the indirect method, the metal inventory of a given process unit is given by subtracting the cumulative reclaim from the cumulative feed. The challenge with this method is that it results in the poor estimation of errors over time and requires major adjustments to estimate the produce. These adjustments are likely to impact the financial performance of the company. The redundant method uses both direct and indirect methods to reach the redundant data set.

Due to the redundant data set, the accuracy attributed to each measurement variable can be assessed and possible detection of systematic errors. The challenge with the redundant method is the data processing approach involving data reconciliations (Bragejeodzgaua.2010). Based on the three methods of process inventory measurements discussed in this chapter, it was concluded that the preferred method for implementation is the redundant method. This is because it uses both direct and indirect methods. Also, the accuracy for all the measurement variables can be assessed as well as the detection of systematic errors.

10.1.7 Chapter Seven: Case study: Real-time material tracking

The seventh chapter provided a case study for real-time material tracking in a typical mechanised underground mine. Critical measurement points where ore variables including tonnage, grade, product content, fragmentation, density, moisture content, can be measured, monitored and tracked were depicted in Figure 7.2. Various data processing and presentation techniques including the Six-Sigma methodology, the lean process improvement and the TOC process improvement approach was discussed.

Basic tools used in Six-Sigma includes a check-sheet, histogram, cause and effect diagram, flow chart, scatter plot, and control graph. Some examples of the application of these tools was depicted in the histogram developed for a stoping analysis year to date graph for Mine A is shown in Figure 7.4; a scatter plot and correlation diagram for gold duplicate values and gold original values in Figure 7.8; and a grade control graph that depicts grade analysis in Figure 7.9. In summary, the lean process improvement methodology focusses on improvement of a process by eliminating wasteful practices. The TOC is based on a principle that in every system there is a constraint/bottleneck that prevents the system from functioning at its best. A five-step thinking process was developed in the TOC approach to enable the invention of simple solutions to complex problems. In terms of identifying operational bottlenecks in an ore flow system, some of the constraints identified was listed in Table 7.2. A specific application of TOC known as the SCRUM production flow system developed by Mabote (2016) was discussed. In this production flow system, the entire flow of the production operation can be viewed holistically using colour patterns of the flow over time (Refer to Figure 7.10). This makes it possible to determine at a glance which areas within the operation require immediate attention.

The researcher however recognized that team work is crucial in achieving a successful flow in every system. An understanding of the responsibilities of each worker and the impact of their decisions and actions should be made clear. The discussion of this case study had limitations in terms of the verification and analysis of the data in the context of ore and metal accounting. These shortcomings were addressed in the new knowledge chapter (next chapter) which puts everything together into a framework.

10.1.8 Chapter Eight: Time and spatial tracking of metal content from in-situ to plant entry: A digital mining technology approach

This chapter developed a conceptual framework for the time and spatial tracking of metal content from underground to surface as part of a solution to addressing the limitations in the data verification and reconciliation in ore and metal accounting. A conceptual underground mine where critical measurement points are defined for measurement, monitoring and tracking was established. These critical measurement points were defined as the in-situ stage referred as stage A; the after-blast stage referred as stage B; ore transportation referred as stage C; stage D is the point of tipping ore into bins and orepass; and the final stage E is the point of stockpiling ore on surface/plant entry.

In designing a system for reliable metal accounting for underground mines, an intelligent reconciliation system at each critical measurement point must be established. The processes outlined in the reconciliation system are to measure the variable of interest; determine the discrepancy between the planned and actual measurement; determine the level of impact of the discrepancy for risk control purpose; decide on tolerance limits; and an assessment of compliance to measurement protocols. A decision must be made in terms of the measurement's acceptance or rejection. The system must also generate a report on each measurement variable. An improvement strategy is recommended towards best practice.

The chapter further developed an implementation plan for measuring, monitoring and tracking ore variables including volume/mass/tonnage, grade, fragmentation, density and moisture content, as well as location-based information. The implementation process consists of defining the purpose of the measurement variable; identification of the best technologies/tools/equipment to use; development of a standard operating protocol for technologies/tools/equipment which should be site-specific; and a competency standard for the use of technologies/tools/equipment identified. The implementation process also relied on discussions from previous chapters and annexes to demonstrate some of the concepts.

The next chapter gives an assessment of digital technologies discussed for all the measurement variables to enable the best choice of technologies/tools/equipment that are applicable for each measurement variable.

10.1.9 Chapter Nine: Assessment of the combined digital mining technology approach for ore tracking

This chapter developed a SWOT analysis tool that was used to determine the best technology option for each measurement variable. From the SWOT analysis in Table 9.1, the researcher's opinion is that scanning technologies are the best technologies for volume and subsequently mass measurement because they are fast and reliable. As compared with traditional total stations, they do not necessarily require targets to work with which makes remote surveying possible by one person. The researcher, however, opines that traditional total stations are still relevant for accurate positional surveys until a time when the scanning technologies can do accurate positional surveys.

Also, the researcher opines that the best option for metal content is the grade analyser. Although a grade analyser is presently not available, the researcher believes the existence of such a digital tool would enhance the process of grade measurements as well as aid in eliminating human inherent errors which are associated with obtaining representative samples for further analysis in a laboratory. The sampling method for grade measurement is however still appropriate.

Furthermore, the SWOT analysis diagram in Table 9.1, revealed that the DIAT systems remain a significant and cost-effective tool for measuring monitoring and tracking fragmentation in a real mining environment. However, because of the issues with accuracy discussed under the weaknesses and threat section of Table 9.1, there is a need to conduct digital measurements alongside the traditional sieving method of fragmentation to ensure measurements are accurate and reliable.

It was deduced that the density and moisture content measurement is based on the physical characteristics of the ore body and practical conditions of the specific site. Moisture content is usually determined from a laboratory setting and later under defined conditions in an oven over a specific period of time to obtain the dry mass and subsequently the moisture content. In the development of standard operating protocol measurement monitoring and tracking, site conditions should be taken into consideration. The use of a QAQC document to ensure the accuracy and reliability of the measurements should also be used. A typical example is the use of standard reference materials to determine the accuracy and precision of measurements.

It can be deduced that the best technology option for material location measurement, monitoring and tracking is the real-time satellite tracking which is not existent. Such a technology would enable the location of physical ore parcels to be measured, monitored and tracked to the smallest detail. However, current location tracking technologies such as RFID, high definition sensor technologies are still great for location measurement monitoring and tracking.

The chapter concludes with the researcher's conceptualization of a CDMT approach with specific reference to a hard rock mining environment (Figure 9.7). This consists of the various stages of tracking broken ore variables at the in-situ stage, after blast stage, during ore transportation, at ore tipping points such as bins/ore passes and stockpiling on surfaces. At every stage of metal content tracking a decision has to be made for which technologies or tools are applicable at each stage of the tracking (SWOT analysis discussed in this chapter is useful for best practice determination of technologies). In the researcher's conceptualization of a CDMT approach in Figure 9.7, an action is required in terms of the development of a standard operating protocol and competency standards for the technologies or tools selected at the decision level.

The next subsection is a summary of the thesis with general recommendations with regards to findings and highlights on areas for further research.

10.2 Recommendations and further research

This section highlights general recommendations for a digital mining technology approach with focus on the need to re-invent existing technologies/tools and processes beyond their present barriers as well as further research considerations taking into account the stated objectives of this research.

- The initial recommendation is for the implementation process for mass and tonnage, sampling for grade, fragmentation, density and moisture content in section 8.7 of this thesis to be tested and implemented in a real mine. This should be adapted as part of a change management process at a real mine. The conceptual model should also be tested and improved.
- Physical metal/ore parcel tracking from underground to surface can be achieved using satellite technology. Although satellite technology is presently not available in an underground environment, the ability to extend satellite technology to an underground environment would enable the physical ore

parcels to be measured, monitored and tracked in real-time. Information on the location of specific ore parcels and time can be communicated into a control room. This would also enable specific ore parcels to be linked to specific sources from underground and enable various ore types to be measured, monitored and tracked to the smallest detail.

- A need to develop sampling standards for technologies. Currently there are sampling standards when the sample is cut from the ore body but when using technology standards are required in terms of the required sample size to measure. This also includes a standardised QAQC and competency principles for sampling measurements using technology.
- The grade analyser tool for measuring metal content should be re-introduced to enable accurate and reliable grade measurements to be made from underground and reported in real-time through a communication network from underground into a control room.
- There is a need to develop unique skills for the design, installation, operation, maintenance and right equipment selection. This can be done though short courses or postgraduate programs.
- Although there are several handheld technologies for density measurements, the media type for the use of these technologies is limited to liquid and gas excluding solids. A similar technology tool for density measurements (density analyser) in solids should be invented to enable density measurements to be made and reported in real-time.
- The detection of Microdots in the aerosol system are done manually using a magnifying glass or visible under ultraviolet light. It is recommended that the

Microdots technology should be improved to enable automatic detection of Microdots. For example, the use of a sensor reader to automatically read the unique codes in the microdot and transfer this information from an underground environment through a communication network (wireless or cable) into a control room.

- The need to improve scanning technologies so that they can perform positional surveys just as traditional survey instruments.

References

AMIRA P754, 2007. *Metal Accounting Code of Practice and Guidelines: Release 3,* Published by AMIRA International, Australia.

Andersen, D. C. 1999. *Criteria influencing the Mine Call Fator of a Gold Mine*. A project report submitted to the Faculty of Mining Engineering, University of the Witwatersrand, Johannesburg.

Anderson, T., Thurley, M., and Marklund, O., 2007. *Visibility classification of pellets in piles for sizing without overlapped particle error*. 9th Biennial Conference of the Australian Pattern Recognition Society on Digital Image Computing Techniques and Applications (DICTA), Glenelg, 3 – 5 December, pp. 508 – 514.

AngloGold Ashanti mineral resource and ore reserve reports 2010 – 2017.

Bamford, T., Esmaeili, K and Schoellig, A.P., 2016. *A Real-Time Analysis of Post-Blast rock Fragmentation Using UAV Technology*. 6th International Conference on Computer Applications in the Minerals Industries, Istanbul, Turkey. 5-7 October 2016. CAM12016-14.

Beringer, B. 1938. *Underground Practice in Mining*. 2nd edn. Mining Publications Ltd, London. 277 pp.

Bragajewicz, M.J. 2010. *Smart process plants: Software and hardware solutions for data accuracy*(p.464). McGraw Hill.

Brink, A. v. Z, Fourie, F., and Zaniewski, T., 2008. *Continuous monitoring for safety, health and optimisation in South African deep-level mining.* The South African Institute of Mining and Metallurgy. Narrow Vein and Reef 2008.

Bruker elemental cooperation, 2014. [Online] , Available at: http://www.bruker.com/ Acessed on 25th September 2014.

Cashdoller, K.l., and Zlochower, I.A., 1990. *Explosion temperatures and pressures of metals and other elemental dust clouds*. [Online] https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/etapo.pdf Accessed on 22th January 2020

Carlsson, O., and Nyberg, L., 1983. *A method for estimation of fragmentation size distribution with automatic image processing*. Proc. First International Symposium on Rock Fragmentation by Blasting – Fragblast, Lulea Sweden, August 1983, pp. 333 – 345.

Cawood, F.T. 2019. *The Wits Mining Insitute, Welcome to the Mine of the Future. PowerPoint presentation.*

Cawood, F.T. 2015(a). *Reporting of coal reconciling planned with actual. Sandvik International Mining School presentation*, University of the Witwatersrand.

Cawood, F.T. 2015 (b).
Digital mine laboratory prepared for digital mining. PositionIT-March 2015 edition : pp. 26 – 30. [Online] https://www.ee.co.za/wp-content/uploads/2015/03/positionit-march15-p26-30.pdf Accessed on 4th June, 2019.

Cawood, F.T, 2012, *Course notes on the role of the mineral evaluator in MRM*. University of the Witwatersrand, Johannesburg.

Cawood, F.T. and Richards, W.J. 2008. *Standardisation and formalising technical inputs into the mine planning process: A coal mine example*. Journal of the Institute of Mine Surveyors of South Africa, Johannesburg, XXXII (9), 659-673.

Cawood, F. T., and Richards, W.J. 2007. *A review of the role of the coal mine surveyor in South Africa.* Journal of the Southern African Institute of Mining and Metallurgy, 107, 109 -113.

Cawood, F.T. 2003. *Underground face sampling on narrow gold reefs: sampling practice and its impact on the mine call factor on Witwatersrand gold mines – lessons learnt.* Journal of the Institute of Mine Surveyors of South Africa, vol, XXXI, no. 7. Pp. 202-224.

CCOHS, 2017. *Canadian Center for Occupational health and Safety*. [Online] https://www.ccohs.ca/oshanswers/legisl/msdss.html Accessed on 28th August 2017

Ceic, 2019. *USGS Gold Production in South Africa*. [Onlne] https://www.ceicdata.com, Accessed on 10th October 2019.

Centric mining systems, 2017, *A Clear view with Centric*. [Online] www.centricminingsystems.com, Accessed on the 8th August, 2017.

Chakraborty, A.K., Raina, A.K, Ramulu, M., Choudhury, P.B., Dudhankar, A., Jhanwar, J.C. and Jethwa, J.L. 2002. *Development of innovative models for optimisation of blast fragmentation and much profile applying image analysis technique and subsystems utilisation concept in Indian surface coal mining regime*. Project Report, MOC Govt. of India Funded Research Project.

COMRO, 1990. Chamber of Mines Research Organisation Gold Analyser. Image obtained through the assistance of Dr. Declan Vogt.

Creamer media mining weekly, nd. New system for tracking ore. [Online]. https://m.miningweekly.com/article/new-system-for-tracking-ore-2010-09-17/rep_id:3861 Accessed on 20th September 2017.

Cunningham, C.V.V. 1996a. *Optical fragmentation assessment – A technical challenge.* In J.A. Franklin and T.Katsabanis (eds.), Measurement of Blast Fragmentation. Rotterdam, Balkema, pp. 13-19.

Cutler, C. J and Eksteen, J.J., 2006. Variance propagation in toll smelting operations treating multiple concentrate stockpiles. Journal of the South African Institute of Mining and Metallurgy. March 2006. Vol 106. pp. 221-227.

DataDotDNA, nd. DataDot technology USA. [Online]. http://www.datadotdna.com/us/datadot_origins.php. Accessed on 15th November 2014.

Davies, T. A., Lloyd, P. J. D, Roberts, D. A and Rolle, R 1979. *A Portable analyser for measuring gold values in stopes*. COMRO Reference: Project No. GT1V06 Research Report No. 16/79 March 1979.

De Jager, E.J. 1997. *The Analysis of the Mine Call Factor in the Gold Mining, with specific reference to Western Holdings Mine*. Thesis: Ph.D. (Eng), University of the Witwatersrand, Johannesburg.

Deloitte 2013. *Tracking the trends 2013*. [Online]. https://www2.deloitte.com/content/dam/Deloitte/ca/Documents/international-business/ca-en-ib-tracking-the-trends-2013.pdf. Accessed on 10th May, 2013.

Deswik, 2019. *Our Core Software offering*. [Online] https://www.deswik.com/software/ Accessed 20th April, 2019.

DigiMine, 2016. *Implementation model for DigiMine*. Powerpoint presentation at DigiMine Laboratory.

Dunstan, K, Lavin, B, Sanford, R, 2006. *The application of Lean Manufacturing in a Mining environment*. International Mine Management conference. Melbourne, Vic,16-18 October 2006.

Esbensen, K.H. 2003. *50 years of Pierre Gy's Theory of Sampling – WCSB tribute*. Aalborg University Esbjerg, Denmark.

Fallon, N., 2017. *SWOT Analysis: What It Is and When to Use It.* [Online] Available at: http://www.businessnewsdaily.com/4245-swot-analysis.html [Accessed 13 May 2017].

Farr, 2012. *"Election 2012 Is Big-Data Nerds' Gut Punch to Traditional Punditry*, [Online] https://venturebeat.com/2012/11/07/big-data-brigade/

Flitton, T. M. Barnard, A.C., and Spangenberg, I. C. 2009. *Structural problems at sample stations from the face to the ingot*. Assignment in partial fulfillment of the GDE course in Sampling Theory and Practice, School Mining Engineering, University of the Witwatersrand. 16pp.

Fouche, P. 2005, *Development of an RF tracer for use in the mining and mineral processing industry, for ore tracking and blending*, EMMES, Eskom conference centre, South Africa.

Fourie and Zaniewski, 2005. *Blast fragmentation management and its impact on the gold mining process* [Online], https://www.scribd.com/document/239643472/Blast-Fragmentation-Management-SAIMM, Accessed on 8th June, 2016.

G2 CROWD, 2019, *Best spreadsheet software*, [Online], https://www.g2crowd.com/categories/spreadsheets Accessed on 17th April 2019

Gogia, S, Michael, B, Voris, E, Brian, H, Holger, K, Noel, Y, and Dane, A, (2012). The big deal about big data for customer engagement. [Online], https://www.forrester.com/report/The+Big+Deal+About+Big+Data+For+Customers+Engagement/-/E-RES72241 Accessed on 14th July 2016.

Goldratt, E. 2010. *Theory of Constraints*, [Online] file:///E:/Docs/From%20SU/PhD/feedbackFC/Chapters/papers/theory_of_constraints_handbook.pdf, Accessed on 6th July, 2019.

Gore, A.1999. The Digital Earth: Understanding our planet in the 21st century. Photogrammetric and Remote sensing, 65(5), 528-530.

Grey campus, 2019, [Online], DMAIC – A Six Sigma Process Improvement Methodology. https://www.greycampus.com/blog/quality-management/dmaic-a-six-sigma-process-improvement-methodology Accessed on 12th August, 2019.

Gy, P.M. 1979. *Sampling of Particulate Materials, Theory, and Practice. Development in Geomathematics 4*. Elsevier Scientific, Amsterdam.

Gy, P.M. 1992. *Sampling of Particulate Materials: Theory and Practice*. 2nd ed Elsevier, Amsterdam.

Gy, P. 2003. *Sampling of discrete materials – a new introduction to the theory of sampling.* 1. Qualitative approach. Chemometrics and Intelligent Laboratory Systems, vol.74.pp.7-24.

Harrisson, R.N. 1952. *Comment on the mine call factor*. Journal of the Institute of Mine Surveyors of South Africa. Pp. 102-104.

Hoover, T.J. 1933. *The Economics of Mining*. Stanford University Press, California. Pp 547.

Hills, V.W, 2000. *Metal accounting: An Integral part of Mineral Resource Management*, Colloquim of the South African Institute of Mining and Metallurgy, Johannesburg.

Hill, R.F, Garber, W. 1978. *Portable X-Ray for in-situ gold qualification*. [Online] http://ieeexplore.ieee.org/abstract/document/4329411/ Accessed on 21st March 2017.

IBM Corporation, 2016. *Learn about the IBM Watson Health Population Health management system*. [Online] https://www.explorys.com/ Accessed on 20th July 2016.

IMSSA communication, 2015. *Drones in mining.* Email communication from the Institute of Mine Surveyors of South Africa. Accessed on 28th May 2015

IBM, *The four V's of Big Data*, [Online] http://www-01.ibm.com/software/data/bigdata/ Accessed on 14th July 2016.

Intersperience, 2015. *Latest thinking from cross roads of marketing, insight and technology*. [Online] http://www.intersperience.com/article_more.asp?art_id=46. [Accessed on 14th August 2015].

ISixSsigma, 2019. *What is Six Sigma.* [Online], https://www.isixsigma.com/new-to-six-sigma/what-six-sigma/ [Accessed on 12th August, 2019).

Jackson, J.O. 1946. *Mine Valuation: Rand Practice*. Louis Gordon Booksellers. 155 pp.

Janisch, P. R., 1973. *Ore accounting*. *J. Inst. Mine Surv. S.Afr*, p. 237.

Jansen, W., Morrison, R., Wortley, M., and Rivett, T. 2009. *Tracer-Based Mine to Mill Ore Tracking via Process Hold-ups at Northparkes Mine*, Tenth Mill Operators Conference, Adelaide, South Australia.

JKMRC, 2008. *An introduction to Metal Balancing and Reconciliation*, published by Julius Kruttschnitt Mineral Research Centre, University of Queensland, Australia, pp 78;82;198;200;454;520.

Ketelhodt, Von., 2009. *Viability of optical sorting of gold waste rock dumps*. World gold Conference 2009. The southern African Institute of Mining and Metallurgy, 2009.

Kitco, 2016. [Online], https://www.kitco.com/scripts/hist_charts/yearly_graphs.plx, Accessed on 4th August, 2016.

Klein, B., Nadolski, S., Liu, Y., Elmo, D., Scoble, M., Scholar, J., 2011. *Investigation of the Implementation of Sensor-based Ore Sorting Systems at a Block Caving Operation*, [Online] https://www.researchgate.net/publication/315722760_Investigation_into_the_Implementation_of_Sensor-based_Ore_Sorting_Systems_at_a_Block_Caving_Operation , Accessed on 8th March 2016.

Krige, D. G. 1952. *A statistical approach to some basic mine valuation problems In the Witwatersrand*. Journal of the Chemical, Metallurgical and Mining Society of South Africa. Pp. 201-215.

Krige, D. G. 1964. *A review of the impact of statistics on mine valuation in the gold mining industry*. Journal of the South African Institute of Mining and Metallurgy, vol. 1, no. 1.pp. 95-111.

Krige, D.G. 1966. *Two dimensional weighted moving average trend surfaces for ore valuation*. Symposium on Mathematical Statistics and computer applications in ore valuation. Southern African Institute of Mining and metallurgy, Johannesburg. Pp.373 – 380.

Krige, D.G. 1994. *A statistical approach to some basic mine valuation problems on the Witwatersrand*. Journal of the South African Institute of Mining and Metallurgy, Johannesburg. Pp. 373-380.

Lachance, L., Flament, F. 2011. *A new ERA tool for state-of-the-art metallurgical balance calculations*. In the 43rd Annual meeting of the Canadian Mineral Processors. Ottawa, Canada.

Lachance, L., Leroux, D., Flament, F., Gariepy, S., 2013. *Including in-process inventories in the metal accounting of flotation plants.* 46th Annual Canadian mineral processors operators conference, Ottawa, Ontario, January 21-23, 2014.

Lachance, L., Leroux, D., Flament, F., Gariepy, S., 2014. *Including in-process inventories in the metal accounting of flotation plants*. 46th Annual Canadian Mineral Processors Operators Conference, Ottawa, Ontario, January 21-23, 2014.

Laney, D. 2001. [Online] https://blogs.gartner.com/doug-laney/files/2012/01/ad949-3D-Data-Management-Controlling-Data-Volume-Velocity-and-Variety.pdf Accessed on 10th February, 2016.

Lane, A., Guzek, J., Van Antwerpen, W., 2015. *Tough choices facing the South African mining industry*. The 6th International Platinum Conference, *Platinum-Metal for the future.* The Southern African Institute of Mining and Metallurgy, Suncity, NorthWest province South Africa.

Lerm, C., 1994. *Evaluation of chip sampling versus the gold analyser*. Journal of the Institute of Mine Surveyors of South Africa, vol. XXVII, no. 5. Pp. 77-87.

Lipton, I.T., and Horton, J.A., 2014. *Measurement of Bulk density for resource estimation – methods, guidelines, and quality control*. In: C. 30, The AusIMM guide to good practice. 2nd ed. Melbourne: the Australian Institute of Mining and Metallurgy. Pp 97 – 108.

Lixin, W., Yin Z.R., Deng Z.Y., Qi A.W., Yang K.M, 2000. *Research to the mine in the 21st century*: Digital mine. J. China Coal Soc., 25: 337 – 342.

Lixin, W., Zuoru, Y., and Yaping Z., 2003. *Restudy on digital mine: Characteristics, framework, and key technologies*. J. China Coal Society. 28: 1-7.

Lixin W., Wangxi Z., and Ruixin Z., 2004. *Digital mine and the future development of mines in China*. Sci. Technol. Rev., 22:-31

Mabote, k., 2012. *The effective application of the theory of constraints*: Rowland mine shaft – Marikana – Lonmin Case study.

Magri, E. J, and Hawkings, D. M., 1987. *Possible improvements in mine valuation due to the use of the gamma-ray fluorescence gold-ore analyser*, Journal of the South African Institute of Mining and Metallurgy, Vol. 87, no 12, pp 407-423.

Marton, A., and Crookes, R. 2000. *A case study in optimizing fragmentation*. The AusIMM Proceedings, (1), 35-43.

Matheron, G, 1960. Principles of geostatistics. Econ. Geology, vol. 58, 1963.pp.1246 to 1266.

Makhuva, M., Arellno, R.M. Harney, D.M. W. 2014. *Determination of bulk density, methods, and impacts, with a case study from Bronces Mine, Chile.* Applied Earth Science, 123:3,196 -*205,* DOI: 10.1179/1743275814Y.0000000058.

Mckinsey global institute, 2011. *Big data, the next frontier for innovation, competition, and productivity.* [Online] file:///E:/Docs/From%20SU/PhD/feedbackFC/Chapters/MGI_big_data_full_report%20(1).pdf, Accessed on 4th August, 2015.

Meloy, T.P., William M.C., 1992a, *Particle Size Analysis, Ed. N.G. Stanley-Wood and RW Lines*, “Continuous Sieve Cascadography, very narrow band sieve in, Royal society of Chemistry, Cambridge England, pp 514-422.

Meloy T.P., Williams M.C., 1992b. *Predicting Pore size distributions for porous Materials*, Proceeding European symposium particle characterization. Partech 5, Numberg, Mar 24-26, pp 585-592.

Meloy, T.P., Williams M.C., and Kapur, P.C., 1992, *‘Continuous Cascadograhy for Mono Size Particle Production*, ‘Presented 1992 AIME annual meeting , Phoenix, AZ, Feb.

Meloy, T.P., Williams M, C, 1993, *Two-dimensional Packed column Flotation, IMPC*, Sidney, Australia, Proceedings.

Merks, J.K. 2000. *Process simulation with spreadsheet software*. Minerals and metallurgical processing, vol.16.No.2

MicrodotSA, 2014. *Microdot information solutions*. [Online], http://www.microdotsa.info/?page_id=8, Accessed on 10th October 2014.

MineRp, 2019. *Manage your mining data*. [Online] https://www.minerp.com/solutions Accessed on 8th June, 2019.

Mine A ore movement, 2019. Mine ore movement of a typical mechanised mining operation. Unpublished document from the Mechanised mine operation located in Ruistenburg, South Africa.

Minnitt R.C.A., 2010. *The state of sampling practice in the South African minerals industry*. Sampling 2010, Perth, 11-12 May 2010. Australasian Institute of Mining and metallurgy, WA. 20 pp.

Minnitt, R. C. A., 2013. *Grade distribution, poor sampling, and financial consequences*. 6th World conference on sampling and Blending, Peru.

Minnitt, R. C. A., 2014. *Sampling in the South African minerals industry*. Journal of the Southern African Institute of Mining and Metallurgy, Volume 114.

Miningweeklywebsite nd. *New system for tracking ore.* [Online]:http://www.miningweekly.com/article/new-system-for-tracking-ore-2010-09-17 Accessed, 5th July 2018.

Mining data online, 2019. *Mining data solutions*. [Online] https://miningdataonline.com/property/730/Bathopele-Mine.aspx#Production, Accessed 10th June, 2019.

Morley, C., 2003. *Beyond reconciliation – A proactive approach to using mining data*, in Proceedings Fifth Large open pit conference, pp 185-191 (The Australian Institute of Mining and Metallurgy: Melbourne).

Morley, C. and Moller, R. (2005). *Iron ore reconciliation – a case study from Sishen Iron Ore Company*. Proceedings of the Iron Ore Conference, Fremantle, Western Australia, 19-21 September 2005. Australasian Institute of Mining and Metallurgy, Melbourne. pp. 311-318.

Morrison, R. 2008. An introduction to Metal Balancing and Reconciliation. University of Queensland.

Mushaka, S. 2000. *Assessing the impact of Spreadsheet modeling in the field of Geomechanic*. SME Annual Meeting, Feb. 28-Mar.1, Salt Lake City Utah.

Mwansa, S., Dance, A., Annandale, D., Kok, D., and Bisiaux, B., nd. *Integration and optimisation of blasting, crushing and grinding at the Newmont Ahafo operation.* Mine planning principles postgraduate course notes conducted by Wits School of Mining engineering.

NASA, 2016, *Office of the Chief Technologist*, [Online] http://www.nasa.gov/offices/oct/openinnovation/aboutus Accessed on 18th July 2016.

Noy, M. J., 2006. *The latest in online fragmentation measurement – stereo imaging over a conveyor*. *FRAGBLAST 8-Proc*. 8th International Symposium on Rock Fragmentation by blasting, 7-11 May, Santiago, pp. 61-66.

Nozowa, E., Corsini, J., La Rosa, D. D., Valery, W., and Allport, A., 2009. *SmartTag system improvements for increase of ore tracking performance from mine to mill and other applications*. In proceedings 10th Brazilian Symposium on Iron Ore, Ouro Preto, Brazilian Association of Metallurgy, Materials and Mining.

Peterson, K, 2015. CEO of Holomatrix Veridot System, personal communication.

Phillips, G.J., Musick, D.L., 1987. *Mine operations Planning, It's as easy as "1-2-3*". [Online], https://0-www-onemine-org.innopac.wits.ac.za/document/abstract.cfm?docid=9628&refresh=78195 Accessed on 8th March, 2018

Pitard, F.F. 1993. *Exploration of the nugget effect. Geostatistics for the next century*. An international forum in Honour of Michel David's Contribution to Geostatistics. Dimitrakopoulos, R. and David, M. (eds). Kluwer Academic Publishers, Boston.

Pitard, F.F. 2009. *Theoretical, practical and economic difficulties in sampling for trace constituents*. Proceedings of the Fourth World conference on sampling and blending. Southern African Institute of Mining and Metallurgy, Johannesburg. Pp.3-12.

Position IT, Jan/Feb 2016. *The geo-informatics, surveying, GIS, mapping, and location-based services journal for Southern Africa*. The Journal of GISSA, IMSSA and SAGI.

Quantcast File System, 2016. *Big Data, Smaller Bills*, [Online] https://www.quantcast.com/about-us/quantcast-file-system/ Accessed on 15th July 2016.

Ranker, 2019. *The best spreadsheet software, Programs, and applications*, [Online], https://www.ranker.com/list/spreadsheet-programs-applications-systems-and-platforms/reference Accessed on 15th April 2019.

Raina, A. K, 2013. *A history of digital image analysis technique for blast fragmentation assessment and some Indian contributions*. Measurement and analysis of blast fragmentation – Sanchidrian and Singh (Eds) © 2013 Taylor and Francis Group, London, ISBN 978-0-415-62140-3.

Reinders, B. J, 2013. *Ore tracking by Radio Frequency Identification (RFID) tag system on Phakisa Mine.* Final MRM 21 project report submitted to the Wits School of Mining engineering.

Riske, R., Froud, J., Morley, C., Gotte, J., 2007. *The Implementation of Snowden's Reconciliation Software – A case study from Telfer.* World Gold Conference, Cairns, QLD, 22-24 October 2007.

Roelofse, F., 2010. *APPENDIX K: Density measurements of selected samples.* [Online],http://wiredspace.wits.ac.za/jspui/bitstream/10539/8903/13/Appendix%20K%20-%20Density.pdf, Accessed on 28th April 2017

Roman, 1992. *Mass Balances on a Spreadsheet.* For Presentation at the SME Annual Meeting Phoenix, Arizona. February 24-27,1992.

Rowland, R. 1966. *Broken ore sampling*. Symposium on Mathematical Statistics and Computer Applications in Ore Valuation. South African Institute of Mining and Metallurgy, Johannesburg. Pp. 324-326.

Rowland, R. and Sichel, H.S. 1960. *Statistical quality control of routine underground sampling*. Journal of the South African Institute of Mining and Metallurgy, Johannesburg. Pp.324-326.

Sanchidrian, J.A., Segarra, P., Lopez, L.M. and Oucheterlony, F.2009. *Evaluation of some distribution functions for describing rock fragmentation data*. In J.A. Sanchindrian (ed.) Proc 9th Inst. Symp. Rock Fragmentation by Blasting. Leiden: CRCPress/Balkema, pp. 239-248.

SAMREC. (2016). *South African Mineral Resource Committee The South African Code for the Reporting of Exploration Results, Mineral Resources, and Mineral Reserves*. 2016 Edition. Prepared by the SAMREC Committee under the Joint Auspices of SAIMM and GSSA).

Salter, J.D. and Wyatt, N.P.G, 1991. *Sorting in the minerals industry: Past, Present, and Future*, Mineral Engineering, vol. 4, nos.7-11, 1991.pp.779-796, Pergamon Press, Great Britain.

Sarbanes-Oxley Act, 2002. *Public Company Accounting Reform and Investor Protection Act of 2002*. 107th Congress of the United States of America at the Second Session, Washington DC, USA, 23rd January 2002.

Search business analytics, 2019. *Big data analytics*. [Online], https://searchbusinessanalytics.techtarget.com/definition/big-data-analytics, Accessed on 5th September 2019.

Sichel, H.S., 1947a. *Mine valuation and maximum likelihood*. MSc dissertation, University of the Witwatersrand.

Sibanye-Stillwater, 2019. [Online], https://www.sibanyestillwater.com/business/southern-africa/pgm-operations/rustenburg/, Accessed on 5th August 2019.

Sichel, H.S, 1947b. *An experimental and theoretical investigation of bias in mine sampling with special reference to narrow gold reefs*. Transactions of the Institute of Mining and Metallurgy, vol. 56.p.403.

Sikmus, R, Dance, A, 2009. *Tracking Hardness and Size: Measuring and Monitoring ROM ore Properties at Highland Valley Copper*. Mine to Mill, Brisbane, Queensland.

Simon, P. 2014. *A retail BI Case Study*, [Online] www.philsimon.com/blog/emerging-tech/bi/a-retail-bi-case-study/ , Accessed on 19th July 2016.

Sims, J.M.F. 1980. *Application of portable delayed nertron activation analysis equipment in the evaluation of gold deposits*. [Online] https://scholarworks.alaska.edu/bitstream/handle/11122/2152/mirl_of80_05.pdf?sequence=1 . Accessed on 21st March 2017.

Smartdraw, 2019. Flowchart. [Online] https://www.smartdraw.com/flowchart/, Accessed on 10th June, 2019.

Snowden, nd. *Supervisor*. [Online] *https://snowdengroup.com/software/,* Accessed on 18th April 2017.

Spangenberg, I., 2012. *The Status of Sampling Practice in the Gold Mining Industry in Africa*, Dissertation: MSc (Eng) University of the Witwatersnd, Johannesburg.

Statistics how to, 2019. *Statistics for the rest of us*. [Online] https://www.statisticshowto.datasciencecentral.com/accuracy-and-precision/ Accessed on 20th April 2016.

Springett, M.,1993. *Solving open pit grade control problems*. Innovative Mine Design for the 21st Century, Bawden and Archibald (eds), USA, pp. 225-226.

Storrar, C.D. 1981. *South African Mine Valuation*. Published by Chamber of Mines of South Africa, Johannesburg, pp. 219.

Tetteh, M.N.M. 2014. *Mine call factor issues at Iduapriem mine. Working towards a mineral and metal accounting protocol*. MSc research report, University of the Witwatersrand, Johannesburg, pp. 99.

Tetteh, M.N.M and Cawood, F. T. 2014. *Mine Call factor Issues from a surface mine perspective.* Article paper published by EE publishers in Position IT.

Tetteh, M.N.M. and Cawood, F.T (2017), *Design considerations for accurate coal measurements points: Towards accurate reconciliation for integrated mine planning*, Journal of the Southern African Institute of Mining and Metallurgy, Volume 117.

Thurley, M. J. 2009. *Fragmentation size measurement in LHD buckets using 3D surface imaging*. FRAGBLAST 9-Proc. 9th International Symposium on Rock Fragmentation by Blasting, Granada, 13-17 September, pp. 229-237.

Thurley, M. J 2011. *Automated online measurement of limestone particle size distributions using 3D range data*. Journal of Process Control 21 (2): 254-262.
Truscot, S.J., Mine Economics. 2nd edition. Mining Publications Ltd, London. 366 pp.

UMAT, 2014. *Density calculation method and procedure.* Unpublished document from the geological engineering laboratory of the University of Mines and Technology Tarkwa, Ghana.

UNESCO World Heritage Centre, 2016. *Decorated Cave of Pont d'arc, known as Grotte Chauvet-Pont d'arc, Ardeche*. [Online] http://whc.unesco.org/en/list/1426 Accessed on the 10th of August 2016.

Van der Merwe, J. W., and Andersen, D. C., 2013, *Applications and benefits of 3D laser scanning for the mining industry*. Journal of the South African Institute of Mining and Metallurgy, 2013.

Veridot, 2016. *Veridot DNA Asset*, [Online], http://ww2.veridot.co.za/wp-content/uploads/2017/05/Veridot-FAQ.pdf, Accessed on 8th August 2016.

Ward, O. M, Grinstein, G, Keim, D. 2015. *Interactive Data Visualization: foundation, techniques, and applications,* Second Edition – 360 Degree Business. A.K. Peters Ltd, Natick, MA, USA c2015, ISBN: 1482257378978148225737З.

Williams, M.C., Meloy, T.P., Rulaka, A., 1991. *An analysis of Two-dimensional vibrating tables*,' Presented 2nd Int. The sum on advances in fine particle processing, July 29 – August 2, san Jose, CA.

Williams, M.C., Meloy, T.P., Rulaka, A., 1993. *Vibrating Tables – A two-dimensional Network Analysis*, 'accepted 1992 Powder Technology.

Williams, M.C., Meloy, T.P. and Tarshan, M., 1995. *Spreadsheet solution of separation processing networks: Grid representations of networks*. Minerals and Metallurgical Processing.

Wills, B.A, 1992. *An introduction to the practical aspects of ore treatment and mineral recovery*, Camborne School of Mines, Cornwall, UK, Mineral Processing Technologies –5th edition, Pergamon Press. 1992.
WMI Mining 4.0 Presentation, 2019.

Woodhall, M. and Strydom, E, 2010. *Spatial information management form multidisciplinary data.* The 4th international Platinum conference, Platinum transition, "Boom or Bust', The Southern African Institute of Mining and Metallurgy, 2010.

Wortley, C.M.G, 2009. *Mass measurement for metal accounting – Principles, practice, and pitfalls*. Fourth World Conference on Sampling and Blending. The South African Institute of Mining and Metallurgy, 2009.

Wotruba, H.2006. *Sensor Sorting Technology – is the minerals industry missing a chance?* XXIII International Mineral Processing Congress, Istanbul, 2006. pp.21-30.

Xuedong D., Lina, Y., Xinming, L., and Jiangtao Ji, 2010. *Overview of Digital Mine*, Information Technology Journal 9(6): 1241-1245, 2010, ISSN 1812-5638, © 2010 Asian Network for Scientific Information.

Yaowei, M., Shengli T., and Shandong W., 2009. *Research on framework and evolution process of digital mine*. Modern Mining, 6: 64-66.

Annexes

Annex A1: Ore flow balance sheet

Category	%	Mass(t)	Grade(g/t)	Content(g)
Pay ore reserve				
+ NIR				
+ Unpay ore reserve				
+ Other sources stoping				
+ Stope reclamation				
+ Stope Development				
Total broken in stopes				
- Sorted and packed in stopes				
Trammed from stopes				
+ Reef development				
- Reef in ballast				
- Development ore sorted				
total reef Trammed				
+/- Discrepancy				
Hoisted as reef				
+ Shaft bins (beginning of the month)				
Total in shaft bins for the month				
- Shaft bins (end of the month)				
Total from shaft bins				
+ Ore from reef dump or stockpile				

To surface sorting plant				
- Sorting				
+ Ore from reef picking plant				
To mill bins				
+ Mill bins beginning of the month				
Total in mill bins for the month				
-Mill bins (end of the month)				
- Tons milled				
+ Tons milled				
+ Slimes treated				
Total tons treated (gold called for)				
Mine Call factor				
Recovery/ Residues				
Recovery plus residues (gold accounted for)				

Source: Adapted from course notes on the role of the mineral evaluator in Mineral Resource Management (MRM) by Cawood, 2012)

Annex A2: Mine production results for one month

Metallurgical Plant		
Tonnes treated	280 000 t	
Residue value	0.55 g/t	
surface sorting	9% of the tonnage received at the sorting plant @ 0,65g/t	
Gold recovered	4 360 kg	
Mill bins		
Beginning of the month	7 400 t @ value of 12,36 g/t	
End of month	9 500 t	
Shaft bins		
Beginning of the month	2800 @15,8 g/t	
End of the month	3000	
The density of solid rock	2,78t/m^3	
Mined from:		
Pay ore Reserves	51 340 m^2 @ 2 127 cm-g/t @ 106 cm	
Not in Reserves	17 554 m^2 @ 1 740 cm-g/t @ 101 cm	
Unpay Block	13 620 m^2 @ 745 cm-g/t @ 96 cm	
Pillar mining	9 428 m^2 @ 1 602 cm-g/t @ 105 cm	27520,332
Stope reclamation	4 000 t @ 15,00 g/t	

Waste from Other Sources	6 000 t	
Gully Vamping	3 774 t @ 7,45 g/t	
Gully waste	15 000	
Waste packed in stopes	13 770 t @ 1,34 g/t	
Reef development	12 000 t @ 4,72 g/t	
Average dimensions of development end	1 000 m	
advance @ 2,4 m wide and 1,8 m high		
Headgear Bins		
Beginning of the month	2 800 t @ 15,80 g/t	
End of month	3 000	
Surface Stockpile		
Beginning of the month	3 500 t @ 13,80 g/t	
End of month	3 100 t @ 15.203	
tonnes		
Pay ore reserve tonnes (ρ = t/v)	151288,712	
Not in Reserves	49288,1212	

Unpay Block	36349,056	
13 620 m^2 @ 745 cm-g/t @ 96		

Source: Adapted from (course notes on the role of the mineral evaluator in MRM by Cawood, 2012)

Annex A3: MCF Calculation and discrepancy calculation

Category	%	Mass(t)	grade(g/t)	content(g)
Pay ore reserve		151289	20,066	3035770,783
+ Not in reserve		49288	17,228	849120
+ Unpay ore reserve		36349	7,760	282083,3854
Pillar mining		27520	15,257	419876,5714
+ Stope reclamation		4000	15	60000
waste from other sources		6000		
Gully Vamping		3774	7,45	28116,3
Gully waste		15000		
Total broken in stopes		**293220**		**4674967,04**
sorted in stopes		13770	1,34	18451,8
Trammed from stopes		**279450**		**4656515,24**
+ Reef development		12000	4,72	56640
total trammed		**291450**		**4713155,24**
- Reef in ballast				
- Development ore sorted				
+/- Discrepancy		18350		
Hoisted as reef		309800	15,214	**4713155,24**
+ Shaft bins (beginning of the month)		2800	15,8	44240
Total in shaft bins for the month		312600	15,219	**4757395,24**
- Shaft bins (end of the month)		3000	15,219	45656,38

Total from shaft bins		309600	15,219	**4711738,86**
+stockpile (beginning)		3500	13,8	48300
Total		313100	15,203	4760038,86
- stockpile (end)		3100	15,203	47129,10
Ore to the surface sorting plant		310000	15,203	4712909,76
- Sorted	9	27900	0,65	18135
+ Ore from reef picking plant		–		
To mill bins		282100	16,642	4694774,76
+ Mill bins beginning of the month		7400	12,36	91464
Total in mill bins for the month		289500	16,533	4786238,76
-Mill bins (end of the month)		9500	16,533	157061,38
- Tonnes milled				
+ Tonnes milled				
+ Slimes treated				
Total tonnes treated (gold called for)		280000	16,533	4629177,38
MCF	97,5			
Plant Recovery Factor	96.6			
Recovery				4360000
Residues			0,55	154000,00
Recovery plus residues (gold accounted for)				4514000,00

Source: Adapted from course notes on the role of the mineral evaluator in MRM by Cawood, 2012

Annex A4: veridot MSDS

1. Chemical product and Company information	**2. Composition of ingredients**
Product identity: Veridot Supplier: Holomatrix Proprietary (PTY) Limited Company (Ltd) Address: 17 Grasmere Street, Morning side, Durban, 4001 Emergency contact: 0825236352 Email address: lorell@holomatirx.co.za Telephone number: 0313121130 Facsimile Number: 0862318005	The following hazardous components are contained in the mixture: Butane propellant, Polyester resin, Propan-2-one, 2-Butoxyethanol, Xylenol, Nitrocellulose, Isopropanol, Ethanol, Dioctyl Phthalate. Each component has a unique CAS no and is classified according to SANS 10265 in terms of its percentage by mass and risk phrases.
3. Hazard Identification	**4. First-aid measures**
Important hazards include human health (harmful by inhalation and in contact with skin), environment (May have short-term environment effects, physical and chemical (Highly inflammable). Precautionary statements[39] are given to prevent injury or harm.	Exposure can be through inhalation leading to irritation, and narcotic issues and affect the central nervous system (CNS). Move to fresh air and in case of discomfort, seek medical attention. Contact with skin can lead to dermatitis. Use hand cleaner/soap and water. Take off contaminated

[39] Including keep out of children; keep away from sources of ignition; after contact with skin, wash immediately with soap and water or use appropriate hand cleanser; take precautionary measures against static discharges; in case of insufficient ventilation, wear suitable respiratory equipment. If swallowed seek medical attention immediately and show

	clothing and if discomfort persists, seek medical attention. In case of contact with the eye, rinse immediately with plenty of water for at least 15 minutes and keep eyelids opened. Seek medical advice if symptoms persist.
5. Handling and storage -	**6. Exposure control or personal protection**
Technical measures: Product should always be used in well-ventilated areas. **Precautions:** Pressurised container-protect from sunlight and do not expose to temperatures exceeding 50°C. Do not pierce or even burn even after use. Keep the product away from sources of ignition. The container should not be used in confined spaces, especially close to the source of ignition. **Safe handling advice:** As the propellant and concentrate are both flammable and can have narcotic and CNS effects, the build-up of dangerous	Permissible concentrations of ingredient compositions in terms of TWA OEL-RL[40] and OEL-RL STEL[41]. Engineering measures recommends the use in well-ventilated areas. Personal protective equipment includes **Respiratory protection** (in case of insufficient ventilation, use suitable respiratory protection). Hand protection (recommends the use of barrier cream and impervious gloves when spraying for long periods. **Eye protection** (Use appropriate eye protection). **Skin and body protection** (Wear appropriate protective clothing and do not spray towards face or body).

container/label; use only in well-ventilated areas; pressurised container; protect from sunlight and do not expose to temperatures exceeding 50°C; do not pierce or burn even when empty; do not spray near naked flame or incandescent material; no smoking ; After contact with skin, wash immediately with soap and water or use appropriate hand cleanser; in case of insufficient ventilation, wear suitable respiratory equipment; use only ad directed (Holomatrix MSDS version 2.14 – 17 Aug 2016)

[40] Time weighted average-occupational exposure limit-recommended limit expressed in mg/m^3

[41] Occupational exposure limit-recommended limit short-term exposure limit expressed in mg/m^3.

concentrations of propellant is possible. Follow all label safety warnings even after container is empty.	
7. Physical and chemical properties	**8. Stability and reactivity**
Appearance (Pressurised aerosol); Form (Fine Mist); Colour (Clear Liquid); Odour (Pungent); PH (Neutral); Melting/Freezing point; May start to solidify at -70.4°C (-94.7°F); Boiling point (59°C) (concentrate); Flash point (-20°C (Closed cup, concentrate); Vapour pressure (16602 hPa (20°C, solvent); Density (0.935 g/mL (concentrate); Solubilities (Insoluble in water, soluble in esters, ketones and glycol ethers); Auto-ignition temperature (the lowest known value is 238°C); Flammability (soil, gas- Highly flammable); Viscosity (<20" Ford Cup #4); Volatility (100%(v/v), Methyl Ethyl Ketone (MEK); Weighted average 126%(v/v)100%(w/w)	The product is stable under normal conditions of use. Condition to avoid include protection from sunlight and do not expose to temperatures exceeding 50°C. Extreme temperatures can occur in motor cars and near ovens and fireplaces. Do not place in contact with hot surfaces or near naked flames. Do not pierce or burn even after use. Do not spray on a naked flame, onto or near the fire, or any incandescent material such as an electric fire. The product is incompatible with oxidizing agents, acids and bases. Anticipated hazardous not known.

9. Toxicological information	10. Ecological information
The toxicity of the product has not been determined. Hazard identification in section 3 was derived from the known effects of the individual ingredients and their concentration in the product.	The product's eco-toxicity has not been assessed. Not expected to have short-term environmental effects as none of the components are classified for environmental effects. No data is available for persistence/degradability, bioaccumulative potential and mobility in soil.
11. Disposal considerations	**12. Transportation information**
Waste from residues: Expel propellant completely by inverting container (in newspaper or scrap cloth) and holding down spray button. Dispose of soiled newspaper or cloth in accordance with relevant National, Provincial and Local Government regulations. For further information, contact your local waste authority. In the case of contaminated container/packaging, aerosol containers may be disposed of with domestic or industrial waste or offered for recycling.	United Nation (UN) number (1950); proper shipping name (Aerosols); UN classification (2.1); packing group(-); marine pollutant (no); Land –Special provisions (63,190,227,327), limited quantity (1L); Sea-Special provisions (63,190,227,327, 959), limited quantity (1L), EmS[42] (F-D[43], S-U[44]); Air – proper shipping name: Aerosols, flammable.

[42] Emergency Schedules
[43] Fire Schedule Golf (F-G) Water reactive substances
[44] Spillage Schedule Uniform (Gases – flammable, toxic or corrosive)

Do not pierce or burn after use, even when apparently empty. Protect from sunlight and do not expose to temperatures exceeding 50°C.	
13. Regulatory information	**14. Other information**
The product is classified as Flammable (F) and Harmful (Xn).	The information provided so far is based on the best available technical knowledge of the product concerned and given in good faith. Attention is drawn to amongst other things, the element of risk consequent to use of the product for the purpose other than that for which it was intended. The document does not remove the need of the recipient to fully understand and apply statutory requirements. It is the recipient's sole responsibility to take due precautions relative to the use of the product. All information contained herein is included only to assist the recipient in fulfilling his or her statutory duty connected with using hazardous materials. The list of information must not be considered as exhaustive and does not exonerate the recipient from taking other precautions described in documents other than the ones mentioned with regards to the storage and use of the product for which the recipient remains solely responsible.

15. Fire-fighting measures	16. Accidental release measures
Extinguishing media: CO_2[45] dry powder. Fog to cool and control. Do not use water jets. **Specific Hazards:** All aerosols are pressurized products and will eventually burst if exposed to very high temperatures or fire. They will then release an extremely propellant flammable gas (butane). They can form explosive/air mixture. Static discharge hazard. **Protection of firefighters:** Requires self-contained breathing apparatus and suitable protective clothing.	**Personal precautions:** keep the area well ventilated. Remove sources of ignition. Environmental precautions: keep out of drains and sewers. Damaged or leaking aerosols should be separated and safe place and away from sources of ignition. If large quantities are involved, the manufacturer should be contacted in order to agree on a safe method of disposal. **Method of clean up – Minor spill**: Wash residues away with water and detergents. Major Spill: Contain and collect spilled product using a suitable absorbent material such as vermiculite. Shovel material into a clean, dry labelled container and close lid. Consult your local waste authority for advice on disposal.

Source: (Adapted from Holomatrix MSDS version 2.14-17 Aug 2016)

[45] Carbon Dioxide

Annex A5: Mine A planned and actual quantity and quality for the production year 2018

Date	Mine A Plan	Mine A Actuals	Mine A Shaft Program Plan	Mine A shaft program actuals	Monthly plan total	Monthly actual total	Planned grade	Best cut grade	Actual grade
01-Jan-18	0	0	198000	178617	280770	236482	2,64	2,69	2,69
02-Jan-18	0	0	198000	178617					
03-Jan-18	0	6094	198000	184710					
04-Jan-18	10780	9644	208780	194355					
05-Jan-18	12250	9384	221030	203739					
06-Jan-18	10780	10171	231810	213910					
07-Jan-18	0	0	231810	213910					

08-Jan-18	10780	9670	242590	223580					
09-Jan-18	12250	9692	254840	233272					
10-Jan-18	12250	10667	267090	243939					
11-Jan-18	12250	9245	279340	253184					
12-Jan-18	12250	8816	291590	262000					
13-Jan-18	10780	9821	302370	271821					
14-Jan-18	0	0	302370	271821					
15-Jan-18	10780	7738	313150	279559					
16-Jan-18	12250	9108	325400	288666					

17-Jan-18	12250	11595	337650	300262					
18-Jan-18	12250	10218	349900	310479					
19-Jan-18	12250	11190	362150	321669					
20-Jan-18	10780	8582	372930	330251					
21-Jan-18	0	0	372930	330251					
22-Jan-18	10780	7951	383710	338202					
23-Jan-18	12250	10789	395960	348991					
24-Jan-18	12250	10955	408210	359946					
25-Jan-18	12250	9158	420460	369104					

26-Jan-18	12250	10763	432710	379867					
27-Jan-18	10780	7670	443490	387537					
28-Jan-18	0	0	443490	387537					
29-Jan-18	10780	8596	454270	396133					
30-Jan-18	12250	9805	466520	405938					
31-Jan-18	12250	9161	478770	415099					
01-Feb-18	12250	10527	12250	10527	282240	266087	2,66	2,73	2,76
02-Feb-18	12250	10450	24500	20977					
03-Feb-18	10780	10407	35280	31384					

04-Feb-18	0	0	35280	31384					
05-Feb-18	10780	10515	46060	41900					
06-Feb-18	12250	9643	58310	51543					
07-Feb-18	12250	11980	70560	63523					
08-Feb-18	12250	12348	82810	75871					
09-Feb-18	12250	13984	95060	89854					
10-Feb-18	10780	8670	105840	98524					
11-Feb-18	0	0	105840	98524					
12-Feb-18	10780	11828	116620	110352					

13-Feb-18	12250	12815	128870	123168					
14-Feb-18	12250	12431	141120	135599					
15-Feb-18	12250	12398	153370	147997					
16-Feb-18	12250	12702	165620	160699					
17-Feb-18	10780	9728	176400	170427					
18-Feb-18	0	0	176400	170427					
19-Feb-18	10780	10990	187180	181417					
20-Feb-18	12250	9737	199430	191154					
21-Feb-18	12250	11538	211680	202691					

22-Feb-18	12250	11116	223930	213807					
23-Feb-18	12250	11665	236180	225472					
24-Feb-18	10780	9807	246960	235278					
25-Feb-18	0	0	246960	235278					
26-Feb-18	10780	9427	257740	244705					
27-Feb-18	12250	11609	269990	256314					
28-Feb-18	12250	9773	282240	266087					
01-Mar-18	12250	10283	12250	10283	275380	261645	2,65	2,73	2,73
02-Mar-18	12250	10418	24500	20701					

03-Mar-18	10780	8924	35280	29626					
04-Mar-18	0	0	35280	29626					
05-Mar-18	10780	10616	46060	40241					
06-Mar-18	12250	10467	58310	50709					
07-Mar-18	12250	10214	70560	60922					
08-Mar-18	12250	11814	82810	72737					
09-Mar-18	12250	12304	95060	85041					
10-Mar-18	10780	9271	105840	94311					
11-Mar-18	0	0	105840	94311					

12-Mar-18	10780	11821	116620	106133					
13-Mar-18	12250	13918	128870	120051					
14-Mar-18	12250	11970	141120	132021					
15-Mar-18	12250	11964	153370	143985					
16-Mar-18	12250	11362	165620	155347					
17-Mar-18	10780	11087	176400	166434					
18-Mar-18	0	0	176400	166434					
19-Mar-18	10780	10045	187180	176478					
20-Mar-18	0	2001	187180	178480					

21-Mar-18	12250	13039	199430	191519					
22-Mar-18	12250	10903	211680	202421					
23-Mar-18	12250	11740	223930	214161					
24-Mar-18	10780	8774	234710	222935					
25-Mar-18	0	0	234710	222935					
26-Mar-18	10780	11041	245490	233976					
27-Mar-18	12250	11523	257740	245499					
28-Mar-18	12250	11056	269990	256555					
29-Mar-18	5390	5090	275380	261645					

30-Mar-18	0	0	275380	261645					
31-Mar-18	0	0	275380	261645					
01-Apr-18	0	0	0	0	256270	245520	2,64	2,7	2,64
02-Apr-18	5390	5307	5390	5307					
03-Apr-18	10780	10423	16170	15729					
04-Apr-18	11760	11012	27930	26741					
05-Apr-18	11760	11997	39690	38738					
06-Apr-18	11760	9816	51450	48554					
07-Apr-18	10780	8501	62230	57054					

08-Apr-18	0	0	62230	57054					
09-Apr-18	10780	8857	73010	65911					
10-Apr-18	11760	11511	84770	77423					
11-Apr-18	11760	11382	96530	88805					
12-Apr-18	11760	10485	108290	99289					
13-Apr-18	11760	11855	50	111145					
14-Apr-18	10780	9893	130830	121038					
15-Apr-18	0	0	130830	121038					
16-Apr-18	10780	11434	141610	132472					

17-Apr-18	11760	11481	153370	143953					
18-Apr-18	11760	11762	165130	155715					
19-Apr-18	11760	11407	176890	167122					
20-Apr-18	11760	10578	188650	177700					
21-Apr-18	10780	9417	199430	187118					
22-Apr-18	0	0	199430	187118					
23-Apr-18	10780	12349	210210	199467					
24-Apr-18	11760	10635	221970	210102					
25-Apr-18	11760	8494	233730	218596					

26-Apr-18	11760	19303	245490	237899					
27-Apr-18	0	0	245490	237899					
28-Apr-18	10780	7621	256270	245520					
29-Apr-18	0	0	256270	245520					
01-May-18	5390	9254	5390	9254	303310	295206	2,69	2,7	2,61
02-May-18	11760	8730	17150	17985					
03-May-18	11760	11036	28910	29020					
04-May-18	11760	9926	40670	38946					
05-May-18	10780	8708	51450	47655					

06-May-18	0	0	51450	47655					
07-May-18	10780	9933	62230	57587					
08-May-18	11760	12372	73990	69960					
09-May-18	11760	12114	85750	82073					
10-May-18	11760	12331	97510	94404					
11-May-18	11760	11337	109270	105741					
12-May-18	10780	7093	120050	112834					
13-May-18	0	0	120050	112834					
14-May-18	10780	10549	130830	123383					

15-May-18	11760	12350	142590	135733					
16-May-18	11760	11054	154350	146787					
17-May-18	11760	12732	166110	159519					
18-May-18	11760	12246	177870	171765					
19-May-18	10780	10155	188650	181920					
20-May-18	0	0	188650	181920					
21-May-18	10780	8324	199430	190244					
22-May-18	11760	10923	211190	201167					
23-May-18	11760	11815	222950	212982					

24-May-18	11760	12966	234710	225948					
25-May-18	11760	11774	246470	237722					
26-May-18	10780	10735	257250	248457					
27-May-18	0	0	257250	248457					
28-May-18	10780	10637	268030	259094					
29-May-18	11760	11512	279790	270606					
30-May-18	11760	11704	291550	282309					
31-May-18	11760	12897	303310	295206					
01-Jun-18	10212	11265	10212	11265	292035	286336	2,69	2,78	2,69

02-Jun-18	10290	8299	20502	19564					
03-Jun-18	0	0	20502	19564					
04-Jun-18	10290	10905	30792	30469					
05-Jun-18	10216	11485	41007	41954					
06-Jun-18	12064	12360	53071	54313					
07-Jun-18	12064	13100	65135	67413					
08-Jun-18	12064	12514	77199	79927					
09-Jun-18	10780	9659	87979	89586					
10-Jun-18	0	0	87979	89586					

11-Jun-18	10780	11185	98759	100771					
12-Jun-18	12064	9064	110822	109836					
13-Jun-18	12064	12603	122886	122439					
14-Jun-18	12064	13307	134950	135746					
15-Jun-18	12064	11847	147014	147593					
16-Jun-18	10780	12827	157794	160420					
17-Jun-18	0	0	157794	160420					
18-Jun-18	10780	10050	168574	170470					
19-Jun-18	12064	11916	180638	182386					

20-Jun-18	12064	12389	192701	194775					
21-Jun-18	12064	10389	204765	205164					
22-Jun-18	12064	12145	216829	217308					
23-Jun-18	10780	10872	227609	228180					
24-Jun-18	0	0	227609	228180					
25-Jun-18	10780	8098	238389	236278					
26-Jun-18	12064	7930	250453	244209					
27-Jun-18	12064	10127	262517	254335					
28-Jun-18	12064	10148	274580	264483					

29-Jun-18	12065	11482	286645	275965					
30-Jun-18	5390	10371	292035	286336					
01-Jul-18	4900	3264	4900	3264	579494	566761	2,69	2,78	2,61
02-Jul-18	9800	9243	14700	12507					
03-Jul-18	11760	11683	26460	24190					
04-Jul-18	11760	10266	38220	34456					
05-Jul-18	11760	10849	49980	45305					
06-Jul-18	11760	12014	61740	57319					
07-Jul-18	9800	7906	71540	65225					
08-Jul-18	0	0	71540	65225					
09-Jul-18	9800	10819	81340	76044					
10-Jul-18	11760	10923	93100	86967					
11-Jul-18	11760	11740	104860	98707					
12-Jul-18	11760	11680	116620	110387					
13-Jul-18	11760	10341	128380	120728					
14-Jul-18	9800	4995	138180	125723					
15-Jul-18	0	0	138180	125723					

16-Jul-18	0	3942	138180	129665					
17-Jul-18	11760	9213	149940	138878					
18-Jul-18	11760	8671	161700	147549					
19-Jul-18	11760	10348	173460	157897					
20-Jul-18	11760	8935	185220	166832					
21-Jul-18	10290	11933	195510	178765					
22-Jul-18	0	0	195510	178765					
23-Jul-18	10290	10467	205800	189232					
24-Jul-18	11760	11309	217560	200541					
25-Jul-18	11760	10797	229320	211339					
26-Jul-18	11760	11291	241080	222630					
27-Jul-18	11760	11310	252840	233940					
28-Jul-18	10290	21796	263130	255736					
29-Jul-18	0	0	263130	255736					
30-Jul-18	10290	10477	273420	266213					
31-Jul-18	11760	10258	285180	276471					
01-Aug-18	11684	10499	11684	10499	294314	290289	2,68	2,68	2,64

02-Aug-18	11684	11419	23368	21918					
03-Aug-18	11684	10306	35052	32224					
04-Aug-18	10500	9471	45552	41695					
05-Aug-18	0	0	45552	41695					
06-Aug-18	10500	11043	56052	52738					
07-Aug-18	11684	12685	67737	65423					
08-Aug-18	11684	10057	79421	75480					
09-Aug-18	0	10674	79421	86154					
10-Aug-18	11684	9386	91105	95540					

11-Aug-18	10500	9526	101605	105065					
12-Aug-18	0	0	101605	105065					
13-Aug-18	10500	10693	112105	115759					
14-Aug-18	11684	10197	123789	125956					
15-Aug-18	11684	10693	135473	136649					
16-Aug-18	11684	12194	147157	148843					
17-Aug-18	11684	11370	158841	160212					
18-Aug-18	10500	13104	169341	173316					
19-Aug-18	0	0	169341	173316					

20-Aug-18	10500	8385	179841	181701					
21-Aug-18	11684	11532	191525	193233					
22-Aug-18	11684	10202	203210	203435					
23-Aug-18	11684	11704	214894	215138					
24-Aug-18	11684	11523	226578	226661					
25-Aug-18	10500	9706	237078	236367					
26-Aug-18	0	0	237078	236367					
27-Aug-18	10500	10438	247578	246806					
28-Aug-18	11684	11427	259262	258232					

29-Aug-18	11684	11705	270946	269938					
30-Aug-18	11684	10157	282630	280094					
31-Aug-18	11684	10195	294314	290289					
01-Sep-18	10500	9960	10500	9960	259868	251219	2,7	2,23	1,98
02-Sep-18	0	0	10500	9960					
03-Sep-18	5250	3397	15750	13357					
04-Sep-18	5250	4303	21000	17660					
05-Sep-18	11812	10327	32812	27987					
06-Sep-18	11812	9480	44624	37467					

07-Sep-18	11812	7981	56436	45448					
08-Sep-18	10500	9997	66936	55445					
09-Sep-18	0	0	66936	55445					
10-Sep-18	10500	9467	77436	64912					
11-Sep-18	11812	11836	89248	76747					
12-Sep-18	11812	10188	101060	86936					
13-Sep-18	11812	12541	112872	99477					
14-Sep-18	11812	12115	124684	111592					
15-Sep-18	10500	13621	135184	125213					

16-Sep-18	0	0	135184	125213					
17-Sep-18	10500	8487	145684	133700					
18-Sep-18	11812	9974	157496	143674					
19-Sep-18	11812	9851	169308	153525					
20-Sep-18	11812	10698	181120	164223					
21-Sep-18	11812	10890	192932	175113					
22-Sep-18	10500	12707	203432	187820					
23-Sep-18	0	0	203432	187820					
24-Sep-18	0	8412	203432	196232					

25-Sep-18	10500	10476	213932	206708					
26-Sep-18	11812	12384	225744	219092					
27-Sep-18	11812	10227	237556	229319					
28-Sep-18	11812	10276	249368	239595					
29-Sep-18	10500	11624	259868	251219					
30-Sep-18	0	0	259868	251219					
01-O°t-18	10780	9494	10780	9494	308700	287628	2,7	2,64	2,66
02-Oct-18	11760	8332	22540	17825					
03-Oct-18	11760	11680	34300	29506					

04-Oct-18	11760	11431	46060	40937					
05-Oct-18	11760	11017	57820	51955					
06-Oct-18	10780	12700	68600	64655					
07-Oct-18	0	0	68600	64655					
08-Oct-18	10780	9794	79380	74449					
09-Oct-18	11760	11491	91140	85940					
10-Oct-18	11760	11565	102900	97505					
11-Oct-18	11760	10043	114660	107548					
12-Oct-18	11760	11702	126420	119249					

13-Oct-18	10780	15008	137200	134257					
14-Oct-18	0	0	137200	134257					
15-Oct-18	10780	9988	147980	144245					
16-Oct-18	11760	10516	159740	154761					
17-Oct-18	11760	10903	171500	165663					
18-Oct-18	11760	11011	183260	176674					
19-Oct-18	11760	9561	195020	186235					
20-Oct-18	10780	13756	205800	199991					
21-Oct-18	0	0	205800	199991					

22-Oct-18	10780	8771	216580	208762					
23-Oct-18	11760	10585	228340	219347					
24-Oct-18	11760	9951	240100	229298					
25-Oct-18	11760	10055	251860	239354					
26-Oct-18	11760	9976	263620	249330					
27-Oct-18	10780	13788	274400	263118					
28-Oct-18	0	0	274400	263118					
29-Oct-18	10780	9931	285180	273048					
30-Oct-18	11760	10042	296940	283090					

31-Oct-18	11760	4538	308700	287628					
01-Nov-18	12000	8885	12000	8885	304000	291818	2,71	2,78	2,73
02-Nov-18	12000	9388	24000	18272					
03-Nov-18	11000	11805	35000	30077					
04-Nov-18	0	0	35000	30077					
05-Nov-18	11000	8867	46000	38945					
06-Nov-18	12000	10402	58000	49346					
07-Nov-18	12000	11616	70000	60962					
08-Nov-18	12000	11280	82000	72242					

09-Nov-18	12000	12621	94000	84863					
10-Nov-18	11000	15510	105000	100373					
11-Nov-18	0	0	105000	100373					
12-Nov-18	11000	11276	116000	111649					
13-Nov-18	12000	11823	128000	123472					
14-Nov-18	12000	11992	140000	135464					
15-Nov-18	12000	11130	152000	146595					
16-Nov-18	12000	10986	164000	157580					
17-Nov-18	11000	14498	175000	172078					

18-Nov-18	0	0	175000	172078					
19-Nov-18	11000	10449	186000	182527					
20-Nov-18	12000	11166	198000	193693					
21-Nov-18	12000	10912	210000	204606					
22-Nov-18	12000	10780	222000	215386					
23-Nov-18	12000	9625	234000	225011					
24-Nov-18	11000	12827	245000	237837					
25-Nov-18	0	0	245000	237837					
26-Nov-18	11000	10021	256000	247859					

27-Nov-18	12000	10742	268000	258601					
28-Nov-18	12000	11972	280000	270573					
29-Nov-18	12000	11239	292000	281813					
30-Nov-18	12000	10005	304000	291818					
01-Dec-18	12700	13632	12700	13632	195314	192759	2,72	2,77	2,84
02-Dec-18	0	0	12700	13632					
03-Dec-18	10500	8296	23200	21928					
04-Dec-18	10974	11909	34174	33837					
05-Dec-18	10974	10793	45148	44629					

06-Dec-18	10974	11341	56122	55970					
07-Dec-18	10974	11251	67096	67221					
08-Dec-18	12700	14714	79796	81935					
09-Dec-18	0	0	79796	81935					
10-Dec-18	10500	10918	90296	92853					
11-Dec-18	10974	10091	101270	102944					
12-Dec-18	10974	9987	112244	112931					
13-Dec-18	10974	10916	123218	123847					
14-Dec-18	10974	10958	134192	134805					

15-Dec-18	12700	15399	146892	150204					
16-Dec-18	0	0	146892	150204					
17-Dec-18	10974	7817	157866	158022					
18-Dec-18	10500	10568	168366	168590					
19-Dec-18	10974	10690	179340	179280					
20-Dec-18	10974	10989	190314	190270					
21-Dec-18	5000	2490	195314	192759					
22-Dec-18	0	0	195314	192759					
23-Dec-18	0	0	195314	192759					

24-Dec-18	0	0	195314	192759					
25-Dec-18	0	0	195314	192759					
26-Dec-18	0	0	195314	192759					
27-Dec-18	0	0	195314	192759					
28-Dec-18	0	0	195314	192759					
29-Dec-18	0	0	195314	192759					
30-Dec-18	0	0	195314	192759					
31-Dec-18	0	0	195314	192759					

Annex A6: Statistical analysis for Mine A Actual tonnages

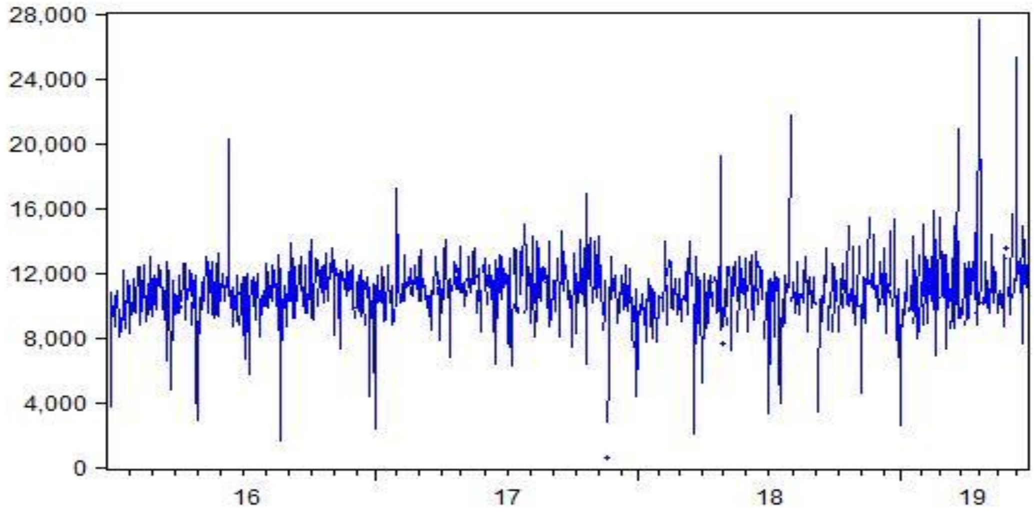
Statistical analysis of the tonnage variables was conducted for the ore movement of an underground mechanised mine referred to as Mine A plan, Mine A Actuals, Mine A Shaft Plan and Mine A shaft actuals (Annex A5). The Mine A Actuals and Plans are the daily tonnages that are planned and measured from daily operations. The shaft Actual tonnage and Shaft plan tonnage are the Mine to Date (MTD) values. The data analysis covers a period from January 2016 to Mid-July 2019.

Annex A6.1: Descriptive statistics - Mine A Actual

	Mine A Actuals
Minimum	607.0000
Maximum	27773.00
Mean	10799.80
Std. Dev	2080.170
Skewness	0.500106
Kurtosis	13.37640
Jarque-Bera	4740.733
P-value of J-B	0.000000

The table above shows the descriptive statistics for tonnage variables for Mine A mine ore actual. The average mine ore movement for Mine A actual is 10799.80 with a standard deviation of 2080.17. The minimum and maximum mine ore movement for actual Mine A was 607.00 and 27773, respectively. The skewness coefficient of 0.5 indicated a positive skewness and the kurtosis value as well confirm asymmetry. The Jarque-Bera value of 4740.733 with a very significant p-value (0.000) confirms that the data is not normally distributed.

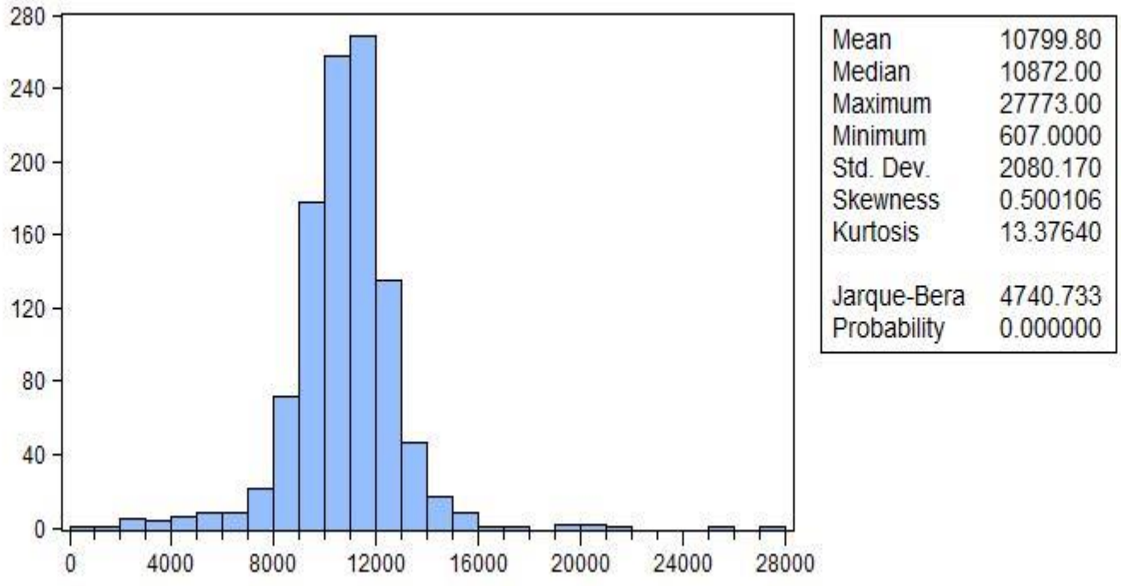
Annex A6.1.1: Time series for Mine A Actual



The figure above presents the pattern of data for the period 2016 to the middle of 2019. The level data shows[46] the tendency to return to its mean with a constant standard deviation. This indicates that the series is weakly stationary. From the Figure below, the mine ore movements for Mine A actuals indicate a non-normal distribution.

[46] The level data refers to the original or raw data

Annex A.6.1.2: Non-normal distribution of Mine A Actual ore movement



Annex A6.2: Unit root, stationarity test

	ADF	PP	KPSS(Intercept)	KPSS (Trend and intercept)
Mine A Actuals	-9.47	-29.42	0.340577	0.161795

The table above reports the results of unit root[47] and stationarity tests. The Augmented Dickey-Fuller (ADF) test and Phillips-Perron (PP) test evaluated the null hypothesis of a unit root test against an alternative of stationarity while the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test evaluates the null hypothesis of stationarity against an alternative of non-stationarity[48].

[47] Unit root test is done to test for stationarity (mean and variance is constant over time) of a time series data
[48] The Augmented Dickey-Fuller (ADF), Phillip Perrons (PP) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) are all used to test for root of a time series.

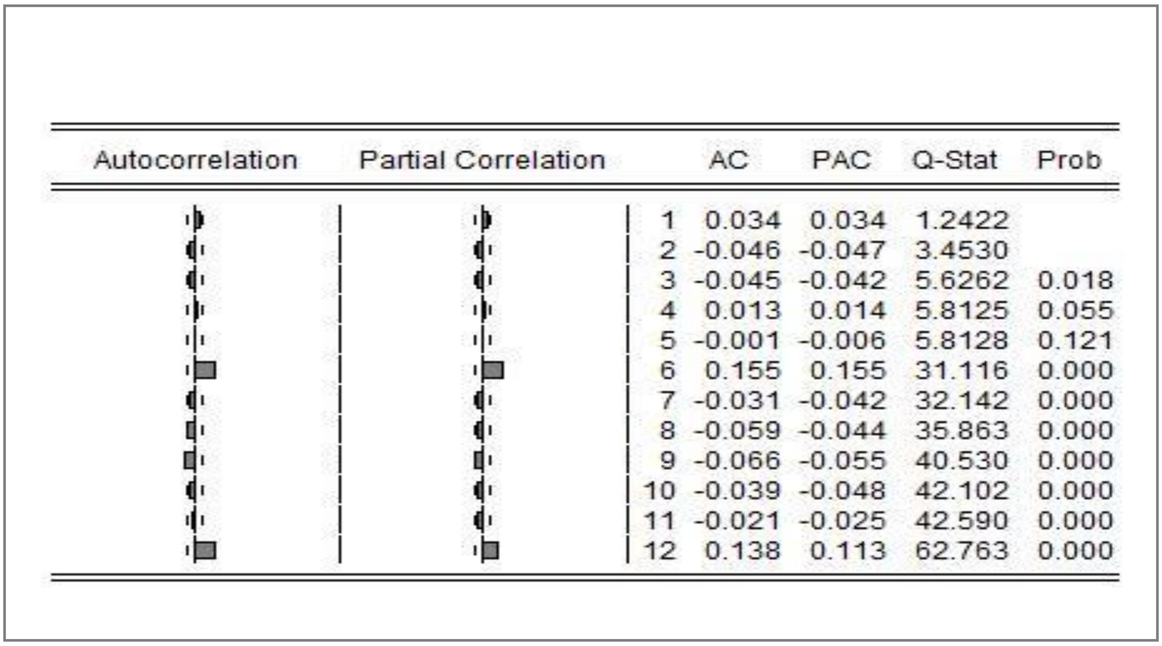
The results indicated that the original Mine A series is stationary at 1%, 5% and 10% according to the ADF, PP, and KPSS (intercept) tests[49]. However, the KPSS (trend and intercept) results indicated stationarity at only 1% and non-stationarity at 5% and 10%.

Annex A6.2.1: Autoregressive term and moving average term

Variable	Coefficient	Std. Error	t-statistics	P-value
c	10796.47	108.7699	99.25975	0.000
AR (1)	0.862288	0.060888	14.16179	0.000
MA (1)	-0.768043	0.071000	-10.81753	0.000
Volatility	180958	74622.56	56.02807	0.000

The autoregressive term AR[50] (1) and moving average term MA[51] (1) in the table above are statistically significant. The moving average term is statistically significant and negative and the volatility term is positive and significant.

Annex A6.2.2: Ljung-Box test



Autocorrelation	Partial Correlation		AC	PAC	Q-Stat	Prob
		1	0.034	0.034	1.2422	
		2	-0.046	-0.047	3.4530	
		3	-0.045	-0.042	5.6262	0.018
		4	0.013	0.014	5.8125	0.055
		5	-0.001	-0.006	5.8128	0.121
		6	0.155	0.155	31.116	0.000
		7	-0.031	-0.042	32.142	0.000
		8	-0.059	-0.044	35.863	0.000
		9	-0.066	-0.055	40.530	0.000
		10	-0.039	-0.048	42.102	0.000
		11	-0.021	-0.025	42.590	0.000
		12	0.138	0.113	62.763	0.000

[49] For the ADF, when the p-value is less than 5%, the series is said to be stationary. Also, with the PP, when the P-value is less than 5%, the series is said to be stationary.
[50] An autoregressive model is one where the current value of a variable depends on previous values and the error term.
[51] Moving average is a model that depends on current and previous values of a white noise disturbance term

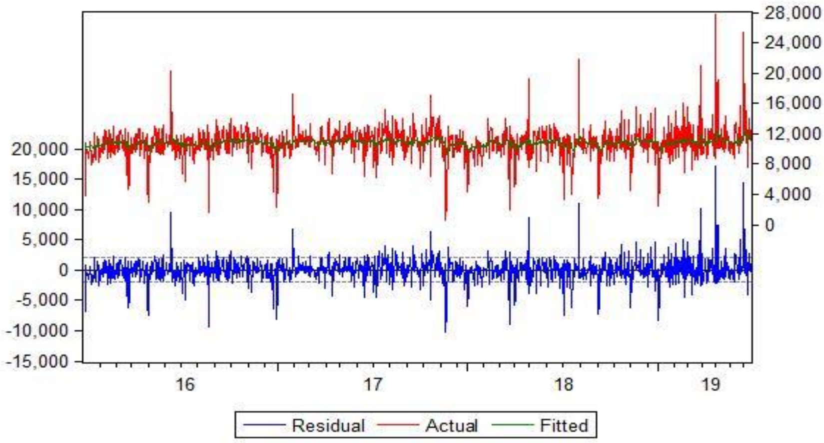
The figure above displays the correlogram for the residuals (Ljung-Box test[52]). From the Figure above, it can be deduced that there are significant autocorrelations at lags 6 and 12.

Annex A6.2.3: Correlogram of squared residuals of the ARMA process

Autocorrelation	Partial Correlation		AC	PAC	Q-Stat	Prob
		1	0.051	0.051	2.7797	0.095
		2	-0.029	-0.032	3.6676	0.160
		3	-0.023	-0.020	4.2115	0.240
		4	0.062	0.064	8.2767	0.082
		5	-0.005	-0.013	8.3071	0.140
		6	0.032	0.036	9.3656	0.154
		7	-0.031	-0.033	10.373	0.168
		8	-0.019	-0.018	10.744	0.217
		9	-0.013	-0.010	10.922	0.281
		10	-0.034	-0.040	12.115	0.277
		11	0.005	0.012	12.138	0.353
		12	0.017	0.014	12.460	0.410

The figure above displays the correlogram for the squared residuals of the ARMA (1,1) process. From the first 12 lags, it can be deduced that there is no autocorrelation since none of the p-values are statistically significant.

Annex A 6.2.4: Residuals of the ARMA model



The figure above displays the residuals of the ARMA (1, 1) model. From the graph, the fitted model does not quite describe the trend in the actual data.

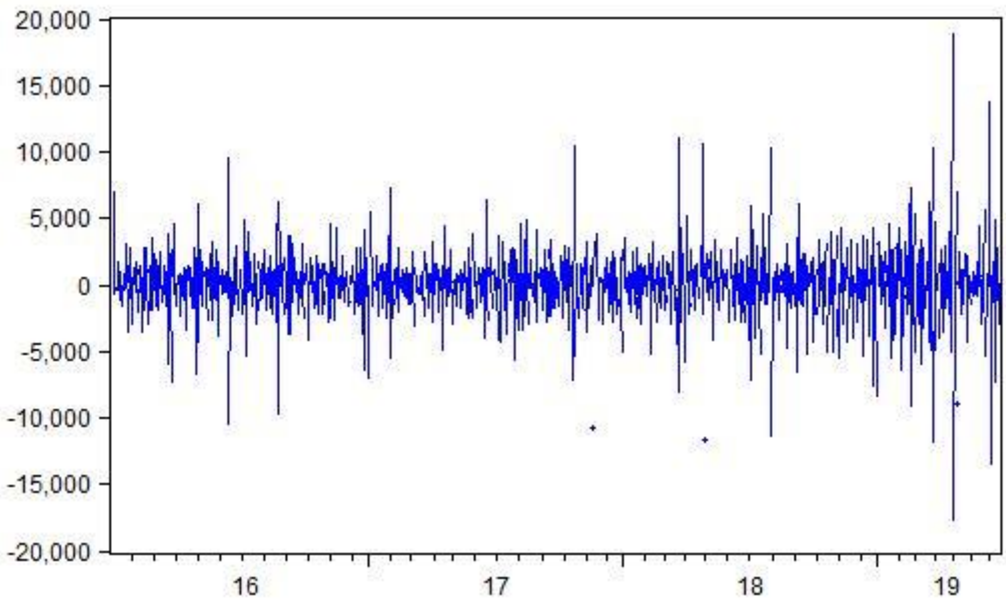
[52] The Ljung-Box test is used to test for lack of fit of a time series model

Annex A6.3: ARCH test 1

	F -statistics	P-value	Obs*R-squared	P-value
Mine A actual	2.7939	0.0949	2.7918	0.0947

There was no evidence of ARCH effect[53] for Mine A actual from the table above (because the P-value of the ARCH test which is 0.0947 is statistically not significant).

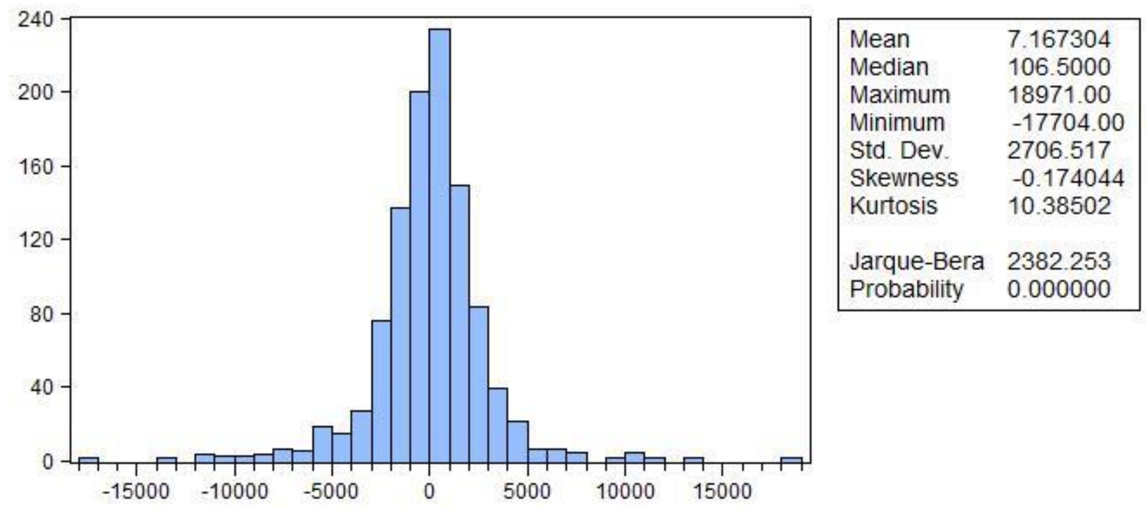
Annex A6.4: Transformed data



The figure above presents the pattern of data for the period 2016 to 2019. The level data shows the tendency to return to its mean with a constant standard deviation. This indicates that the series is weakly stationary. From the figure below, the mine ore for Mine A actuals indicates a non-normal distribution.

[53] The ARCH test is conducted before estimating a Garch model to ensure that the Garch model is appropriate for the data

Annex A6.4.1: Non-normal distribution of transformed mine A actual ore movement



Annex A.6.4.2: Results of the unit root stationarity test

	ADF	PP	KPSS(Intercept)	KPSS(Trend and intercept)
Mine A Actuals	-16.75768	-81.99351	0.027468	0.015218

The table above reports the results of the unit root and stationarity test. The ADF test and PP test evaluated the null hypothesis of a unit root test against an alternative of stationarity while the KPSS test evaluates the null hypothesis of stationarity against an alternative of non-stationarity. The results indicated that the transformed Mine A series is stationary at 1%, 5% and 10% according to the ADF, PP and KPSS (intercept) and KPSS (trend and intercept) tests.

Annex A6.4.3: Auto regressive and moving average model

Variable	Coefficient	Std. Error	t-statistics	P-value
c	1.524435	1.434852	1.062434	0.2883
AR(1)	0.121913	0.024384	4.999668	0.0000
MA(1)	-0.981493	0.007703	-127.4187	0.0000
Volatility	4195252.	74736.44	56.13396	0.0000

The AR(1) and MA(1) in the model are statistically significant[54] (from the table above). The moving average term is statistically significant and negative and the volatility term is positive and significant.

Annex A6.5: ARCH test 2

	F -statistics	P-value	Obs*R-squared	P-value
Mine A actual	4.679394	0.0308	4.667426	0.0307

There was evidence of the ARCH effect for Mine A actual therefore requiring a GARCH model from the table above. A feature noted in the analysis of the data is that the variance of the daily mine ore (Mine A actual) is not constant over time. An irregular series variance over time rationalises the use of GARCH model. There is evidence of volatility clustering as shown in the 1st figure (on Pg. 330). Also, the ARCH effect as shown in Table above justifies using GARCH in modeling the volatility of the mine ore.

The GARCH model was estimated using generalised error distribution.

[54] They are statistically significant because the P-value is less than 0.05

Annex A6.6: GARCH (GED)[55]

Variable	Coefficient	Std. Error	z-Statistic	Prob.
C	4.775531	1.218753	3.918376	0.0001
AR(1)	0.081440	0.025004	3.257121	0.0011
MA(1)	-0.971375	0.003949	-245.9512	0.0000
	Variance Equation			
C	3644832.	351812.4	10.36016	0.0000
RESID(-1)^2	0.147477	0.057315	2.573095	0.0101
GARCH(-1)	-0.110867	0.049599	-2.235275	0.0254
GED PARAMETER	1.027363	0.041887	24.52687	0.0000

R-squared	0.424310	Mean dependent var	7.167304
Adjusted R-squared	0.423206	S.D. dependent var	2706.517
S.E. of regression	2055.517	Akaike info criterion	17.82353
Sum squared resid	4.41E+09	Schwarz criterion	17.85667
Log likelihood	-9314.706	Hannan-Quinn criteria.	17.83610
Durbin-Watson stat	1.919312		

Inverted AR Roots	.08
Inverted MA Roots	.97

The results of the GARCH (1,1) model using the GED distribution is shown in the figure above. The estimates of the model indicate that all the coefficients of mean and variance equations are statistically significant at 5% level. The absolute value of the inverted roots for both AR and

[55] The GARCH model allows the conditional variance to be dependent upon previous own lags.

MA is less than 1 as required with R –squared of about 42% and (AIC and BIC)[56] values at 17.82 and 17.85, respectively.

An ARCH effect test was conducted and results indicated that the variance has been modelled as there was no effect of ARCH from the results in the table below.

Annex A6.6.1: Results of Arch effect

F-statistic	0.123318	Prob. F(1,1043)	0.7255
Obs*R-squared	0.123540	Prob. Chi-Square(1)	0.7252

Date: 09/29/19 Time: 20:49

Sample: 1/04/2016 7/15/2019

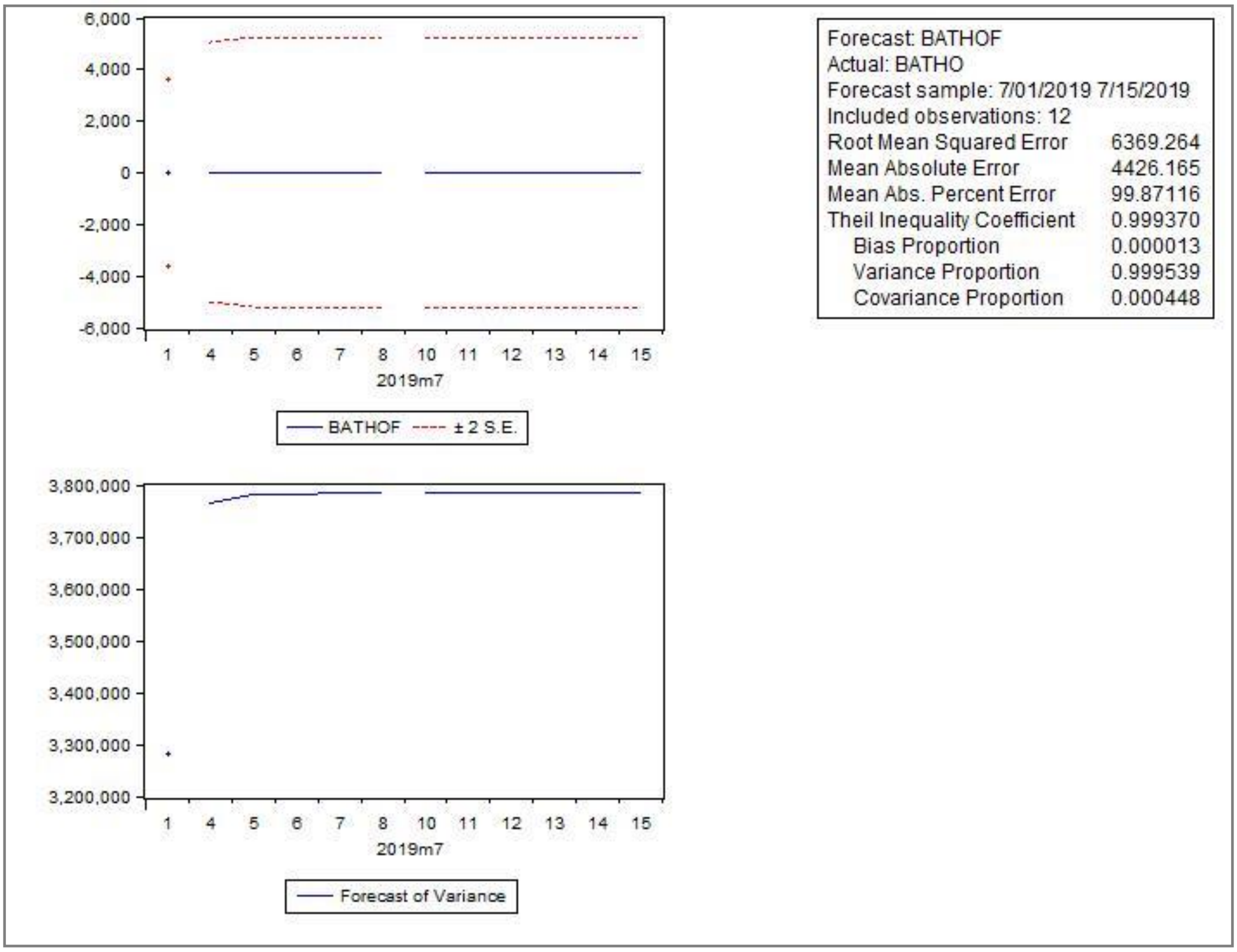
Included observations: 1046

Autocorrelation	Partial Correlation		AC	PAC	Q-Stat	Prob*
| |	| |	1	-0.011	-0.011	0.1238	0.725
| |	| |	2	-0.022	-0.022	0.6258	0.731
| |	| |	3	-0.022	-0.022	1.1206	0.772
| |	| |	4	0.060	0.060	4.9704	0.290
| |	| |	5	-0.007	-0.007	5.0220	0.413
| |	| |	6	0.036	0.039	6.4204	0.378
| |	| |	7	-0.032	-0.030	7.5324	0.376
| |	| |	8	-0.014	-0.017	7.7403	0.459
| |	| |	9	-0.011	-0.010	7.8653	0.548
| |	| |	10	-0.036	-0.043	9.2409	0.509
| |	| |	11	0.003	0.005	9.2488	0.599
| |	| |	12	0.020	0.018	9.6877	0.643

[56] AIC AND BIC stands for Akaike Information Criterion and Bayesian Information Criterion. They are both used to select best models.

Correlogram of the residuals and standardized residuals squared also show non-significant p-values at the first 12 lags indicating no issue of serial correlation from the table above.

Annex A6.6.2: Decomposition of the prediction errors



The Figure above shows a (decomposition of the prediction errors)[57]. The bias proportion (0.000013) which is a measure of the extent to which the mean of the forecast is different to the mean of the actual value is small indicating unbiased forecast.

[57] This is used to test the accuracy of the prediction

Annex A7: Statistical analysis of Mine A Planned tonnage

Annex A7.1 Descriptive statistics Mine A-Planned

	Mine A plan
Minimum	4900.000
Maximum	12700.00
Mean	11018.15
Std. Dev	1010.640
Skewness	-2.920442
Kurtosis	16.95751
Jarque-Bera	9843.909
P-value of J-B	0.000000

The table above shows the descriptive statistics for Mine A plan ore movements. The average mine ore movement for Mine A plan was 11018.15 with a standard deviation of 1010.64. The minimum and maximum mine ore movement for plan Mine A were 4900 and 12700, respectively. The skewness coefficient of -2.920 indicated a negative skewness and the kurtosis value as well confirm asymmetry. The Jarque-Bera value of 9843.909 with a very significant p-value (0.000) confirms that the data is not normally distributed.

Annex A7.2 Unit root, stationarity test

	ADF	PP	KPSS(Intercept)	KPSS(Trend and intercept)
Mine A plan	-6.5912	-20.333	1.610	0.096
Mine A plan (transformed)	-14.22	-37.140	0.0611	0.023

The table above reports the results of unit root and stationarity tests. The ADF test and PP test evaluated the null hypothesis of a unit root test against an alternative of stationarity while the KPSS test evaluates the null hypothesis of stationarity against an alternative of non-stationarity. The results indicated that the transformed Mine A plan series is stationary at 1%, 5% and 10% according to the ADF, PP, and KPSS (intercept) and KPSS (trend and intercept) tests.

Annex A7.3 ARCH test

	F -statistics	P-value	Obs*R-squared	P-value
Mine A plan	32.39	0.000	31.46	0.000

There was a strong evidence of ARCH effect as shown in the table above for Mine A plan indicating that a GARCH model is appropriate.

Annex A7.4 GARCH Models

Variable	Coefficient	Std. Error	z-statistics	Prob.
	Mean equation			
Constant	5.642833	0.049252	114.5717	0.000
AR(1)	-0.110411	0.004850	-22.76478	0.000
MA(1)	-7.23E+08	22141306	-32.66732	0.000
MA(2)	35944908	1561528	23.01906	0.000
MA(3)	4.32E+08	13285716	32.50112	0.000
	Variance equation			
Constant	5.68E-17	6.81E-17	0.833274	0.4047
ARCH(1)	0.701264	0.009072	77.29638	0.000
GARCH(1)	0.239724	0.001890	126.8613	0.000

The basic GARCH (1, 1) result using normal distribution is shown in the table above. The AIC and BIC suggest an ARMA (2,3) as the mean equation. The second equation consists of the ARCH and GARCH terms. The variance equation underscores the high persistence of Mine A plan mine ore with a high ARCH coefficient (0.70) and a low GARCH coefficient (0.24).

The result shows that the coefficient of the ARCH effect is statistically significant at 5% significance level. This indicates that volatility from the previous periods has an effect on current volatility. Similarly, the coefficient of the lagged conditional variance (GARCH) is significantly different from zero, indicating volatility clustering in mine ore for Mine A plan.

Annex A7.5 Students t distribution

Variable	Coefficient	Std. Error	z-statistics	Prob.
	Mean equation			
Constant	-0.551936	0.636878	-0.866628	0.3861
AR(1)	-0.113072	0.188626	-0.599452	0.5489
MA(1)	-1.01E+09	33769909	-29.91576	0.000
MA(2)	1.11E+08	1.56E+08	0.711677	0.4767
MA(3)	3.87E+08	48715354	7.949256	0.000
	Variance equation			
Constant	5.67E-19	3.65E-16	0.001554	0.9988
ARCH(1)	0.364048	0.023902	15.23110	0.000
GARCH(1)	0.718260	0.008509	84.40843	0.000

The basic GARCH (1, 1) result using a student's t distribution is shown in the table above. The AIC and BIC suggest an ARMA (1, 3) as the mean equation[58]. The second equation consists of the ARCH and GARCH terms. The variance equation underscores the high persistence of Mine A plan mine ore with a low ARCH coefficient (0.36) and a high GARCH coefficient (0.72).

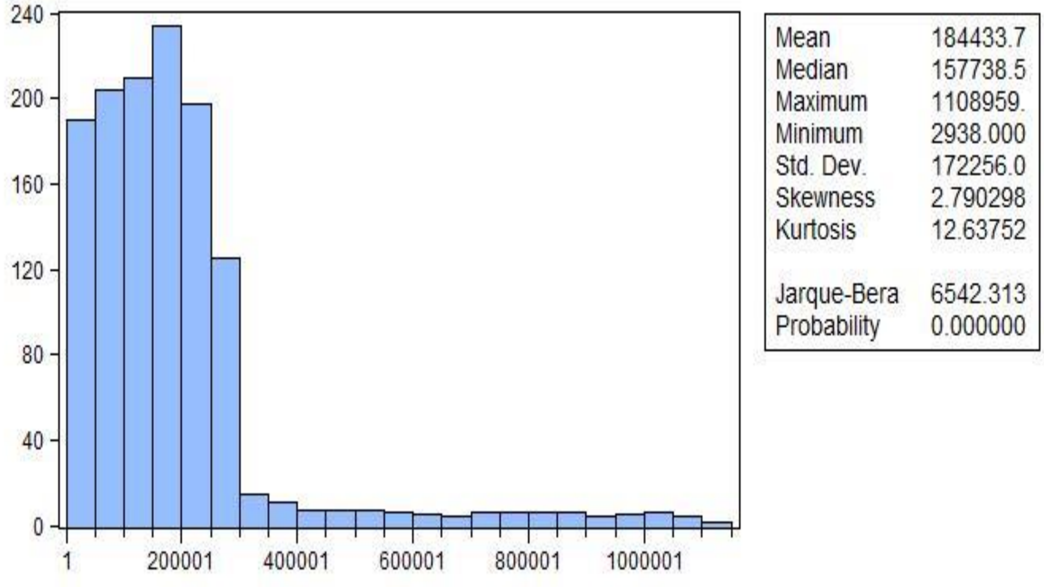
[58] Different models were fitted to the data and the model with the lowest AIC AND BIC was selected. In this case the model with the lowest AIC AND BIC was the ARMA (1, 3).

Annex A8: Statistical analysis for Mine A shaft Actual

	Shaft Actuals
Minimum	2938.000
Maximum	1108959.
Mean	184433.7
Std. Dev	172256.0
Skewness	2.790298
Kurtosis	12.63752
Jarque-Bera	6542.313
P-value of J-B	0.000000

The table above shows the descriptive statistics for each of the mine ore movements at the shaft. The average mine ore movement for the actual shaft was 184433.7 with a standard deviation of 172256. The minimum and maximum mine ore movement for the actual shaft were 2938 and 1108959, respectively. The skewness coefficient of 2.790 indicated a positive skewness and the kurtosis value as well as confirm asymmetry in the figure below. The Jarque-Bera value of 6542.313 with a very significant p-value (0.000) confirms that the data is not normally distributed.

Annex 8.1 Skewness of Mine A shaft actual



Annex A8.2: Unit root, stationarity test

Table 10.1 Unit root, stationarity test

	ADF	PP	KPSS(Intercept)	KPSS (Trend and intercept)
Shaft actual	-3.462505	-2.966	0.9754	0.3373
	-29.46746	-68.12981	0.0588	0.05411

The table above reports the results of unit root and stationarity tests. The ADF test and PP test evaluated the null hypothesis of a unit root test against an alternative of stationarity while the KPSS test evaluates the null hypothesis of stationarity against an alternative of non-stationarity. The results indicated that the transformed shaft actual series is stationary at 1%, 5% and 10% according to the ADF, PP and KPSS (intercept) and KPSS (trend and intercept) tests.

There was a unit root for shaft actual using the KPSS (intercept) and KPSS (trend and intercept) and no unit root using the ADF and PP tests.

Annex A8.2.1: AR and MA models

Variable	Coefficient	Std. Error	t-statistics	P-value
c	0.001652	0.004288	0.385313	0.7001
AR(1)	0.747175	0.050120	14.90771	0.0000
MA(1)	-0.983148	0.013542	-72.59913	0.0000
Volatility	0.330238	0.015399	21.44483	0.0000

The terms AR (1) and MA (1) in the model are statistically significant (Refer to the table above). The moving average term is statistically significant and negative and the volatility term is positive and significant. The inverted AR and MA roots are both positive and smaller than 1. The AIC and BIC of the model are 1.737494 and 1.753756, respectively.

Annex A8.2.2: Ljung – Box test

Date: 09/30/19 Time: 05:41

Sample: 1/04/2016 7/15/2019

Included observations: 1265

Q-statistic probabilities adjusted for 2 ARMA terms

Autocorrelation	Partial Correlation		AC	PAC	Q-Stat	Prob
| |	| |	1	-0.010	-0.010	0.1193	
| |	| |	2	0.024	0.024	0.8624	
| |	| |	3	0.025	0.025	1.6416	0.200
| |	| |	4	0.011	0.010	1.7831	0.410
| |	| |	5	0.003	0.002	1.7967	0.616
| |	| |	6	-0.000	-0.002	1.7970	0.773
| |	| |	7	-0.006	-0.006	1.8390	0.871
| |	| |	8	-0.016	-0.016	2.1698	0.903
| |	| |	9	-0.021	-0.021	2.7503	0.907
| |	| |	10	-0.026	-0.026	3.6224	0.889
| |	| |	11	-0.032	-0.031	4.9220	0.841
| |	| |	12	-0.033	-0.031	6.3325	0.787

The figure above displays the correlogram for the residuals (Ljung-Box test). From the Figure above, it can be deduced that there are no significant autocorrelations for the lag up to 12

Annex A8.2.3: Correlogram of squared residuals

Date: 09/30/19 Time: 05:41

Sample: 1/04/2016 7/15/2019

Included observations: 1265

Autocorrelation	Partial Correlation		AC	PAC	Q-Stat	Prob
| |	| |	1	-0.020	-0.020	0.5318	0.466
| |	| |	2	-0.026	-0.027	1.4058	0.495
| |	| |	3	-0.027	-0.028	2.3503	0.503
| |	| |	4	-0.029	-0.031	3.4305	0.489
| |	| |	5	-0.030	-0.033	4.5533	0.473
| |	| |	6	-0.030	-0.034	5.7041	0.457
| |	| |	7	-0.030	-0.036	6.8847	0.441
| |	| |	8	-0.030	-0.037	8.0661	0.427
| |	| |	9	-0.031	-0.038	9.2540	0.414
| |	| |	10	-0.031	-0.040	10.450	0.402
| |	| |	11	-0.031	-0.042	11.663	0.389
| |	| |	12	-0.031	-0.044	12.892	0.377

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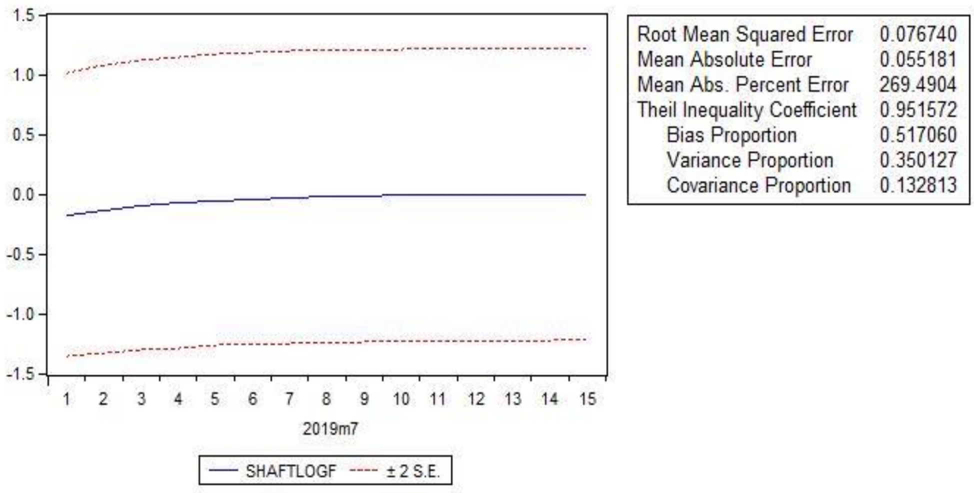
Also, the Figure above displays the correlogram for the squared residuals of the ARMA (1, 1) process. From the first 12 lags, it can be deduced that there is no autocorrelation since none of the p-values are statistically significant.

Annex A8.2.4: Decomposition of prediction errors



The figure above shows a decomposition of the prediction errors[59]. The bias proportion (0.517060) which is a measure of the extent to which the mean of the forecast is different to the mean of the actual value is small indicating unbiased forecast. The root mean squared error is small indicating a good prediction.

Annex A8.3: ARCH test

	F -statistics	P-value	Obs*R-squared	P-value
Shaft actual	0.529759	0.4668	0.530376	0.4664

There was strong evidence of no ARCH effect as shown in the table above for shaft actual indicating that a GARCH model is not required.

[59] The prediction errors is a measure of how well the model predicts the out of sample data.

Annex A9: Statistical analysis for Mine A Shaft Plan

Annex A9.1: Descriptive statistics shaft plan

	Shaft plan
Minimum	4900.000
Maximum	1063404.
Mean	185317.9
Std. Dev	167163.4
Skewness	2.634408
Kurtosis	11.73770
Jarque-Bera	5478.674
P-value of J-B	0.000000

The table above shows the descriptive statistics for the plan mine ore movements at shaft. The average mine ore movement for plan shaft was 185317.9 with a standard deviation of 167163.4. The minimum and maximum mine ore movement for plan shaft were 4900 and 1063404, respectively. The skewness coefficient of 2.634408 indicated a positive skewness and the kurtosis value as well confirm asymmetry. The Jarque-Bera value of 5478.674 with a very significant p-value (0.000) confirms that the data is not normally distributed.

Annex A9.2: Unit root, stationarity test

	ADF	PP	KPSS(Intercept)	KPSS(Trend and intercept)
Shaft plan	-3.79	-3.33	1.028557	0.327988
Shaft plan (transformed)	-24.311	-68.48693	0.058410	0.054758

The table above reports the results of unit root and stationarity tests. The ADF test and PP test evaluated the null hypothesis of a unit root test against an alternative of stationarity while the KPSS test evaluates the null hypothesis of stationarity against an alternative of non-stationarity. The results indicated that the transformed shaft plan series is stationary at 1%, 5% and 10% according to the ADF, PP, and KPSS (intercept) and KPSS (trend and intercept) tests. There was a unit root for the shaft plan using the KPSS (intercept) and no unit root using the ADF, PP tests and KPSS (trend and intercept).

Annex A9.2.1: AR and MA models

Variable	Coefficient	Std. Error	t-statistics	P-value
c	0.001601	0.004627	0.345970	0.7294
AR(1)	0.750861	0.053774	13.96324	0.0000
MA(1)	-0.983363	0.013102	-75.05267	0.0000
Volatility	0.316372	0.016220	19.50559	0.0000

The AR (1) term and MA (1) term in the model are statistically significant (refer to the table above). The moving average term is statistically significant and negative and the volatility term is positive and significant. The inverted AR and MA roots are both positive and smaller than 1. The R squared value is 10.8% with AIC and BIC values of 1.69 and 1.71, respectively.

Annex A 9.2.2: Ljung-Box test

Autocorrelation	Partial Correlation		AC	PAC	Q-Stat	Prob
		1	-0.023	-0.023	0.6842	0.408
		2	-0.026	-0.026	1.5261	0.466
		3	-0.028	-0.030	2.5544	0.466
		4	-0.030	-0.032	3.6854	0.450
		5	-0.030	-0.033	4.8391	0.436
		6	-0.031	-0.035	6.0378	0.419
		7	-0.031	-0.037	7.2663	0.402
		8	-0.031	-0.038	8.4905	0.387
		9	-0.031	-0.040	9.7269	0.373
		10	-0.031	-0.041	10.976	0.359
		11	-0.031	-0.043	12.240	0.346
		12	-0.032	-0.045	13.516	0.333

The figure above displays the correlogram for the residuals (Ljung-Box test). From the figure above, it can be deduced that there are no significant autocorrelations for the lag up to 12.

Annex A9.3: ARCH test

	F -statistics	P-value	Obs*R-squared	P-value
Shaft plan	0.681386	0.4093	0.682099	0.4089

There was no evidence of ARCH effect as shown in the table above indicating that a GARCH model is not appropriate.

Annex A10: GIS for grade variance maps

Annex A10.1: Introduction

This annexure is an implementation for spatial comparison of planned, best cut and actual grade from Mine A for the 2018 production year in GIS (Refer to Figure 7.13 in the thesis). Relevant levels or features were identified and used to digitize the mined-out areas (MOA). Part of this implementation process is to build a spatial database which compares planned and actual quality estimates of the mine for ore reconciliation and metal accounting purpose. It is important to mention here that such analysis is usually done in spreadsheets and not linked to the spatial data set. This annexure gives a description of the data obtained from Mine A, the data cleaning methods used, digitization of the MOA for 2018 production year and the development of the GIS grade variance maps for ore and metal accounting and reconciliation for quality estimates.

Annex A10.2: Data cleaning

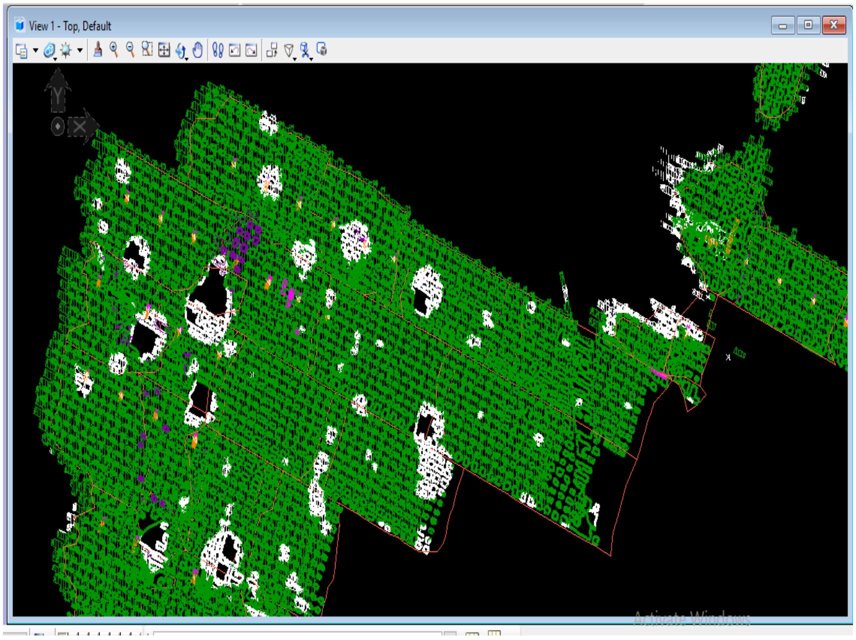
The following data cleaning techniques were employed to ensure there were no unwanted text or values in the data.

- Identification and treatment of blank cells in Mine A mine ore movement 2016-2019 data;
- Identification and treatment of duplicates in the same data;
- linking of coordinate files (planned and actual) with the relevant attribute table.

Annex A10.3: Data description and digitization of mined-out areas

The data used includes the mineA_workings_2017_2018, planned scheduled data for 2018 production year and excel spreadsheet which contains the mine A plan and actual tonnages as well as planned grade[60], best-cut grade[61] , and actual grade[62].

Annex A10.3.1: mineA_workings



Some of these features and their specific naming conventions used at Mine A include the stoping pillar measured; the Stoping pillar adjusted; Development_Slip_profile_fw_lifting; Development_Slip_profile_hw_lifting; Stoping measured reef; Stoping_reef_fw_ripping; Dip plane 2016-2018; Stoping pillars measured 2017-2018. Each of these levels and their descriptions, as well as their consideration in digitizing the MOA, are outlined in the table below.

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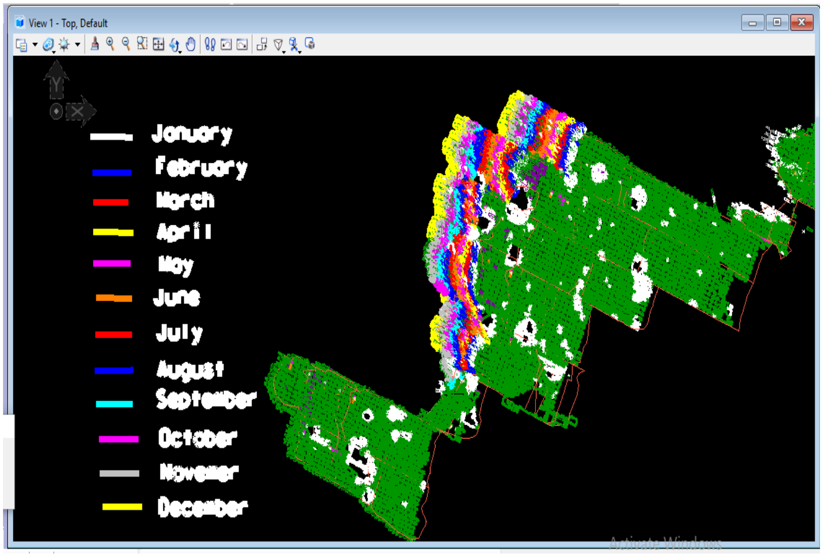
[60] Obtained from the planning budget plan.
[61] Best fit extraction grade with regards to the stratigraphy.
[62] After mining measured by the surveyor.

Annex A10.3.2: Levels and descriptions of MOA

Level	Purpose of level	Consideration for MOA
Stoping pillar measured	Pillars measured by the Surveyor (ground left in-situ and not mined)	The area is included in the MOA.
Stoping pillar adjusted	These are after check surveys or re-measuring the face/pillar position and usually captured on the adjusted level.	The area is included in the MOA.
Development_Slip_profile_fw_lifting	This is the footwall development sliping. Slipping is the blasting done on tip or belt excavations either in the footwall or hanging wall.	Included in the MOA.
Development_Slip_profile_hw_lifting	This is the hanging wall development sliping.	Included in the MOA
Stoping measured reef	This would be the face position measured by the Surveyor.	Included in the MOA
Stoping_reef_fw_ripping	This is the footwall stope sliping	Included in the MOA
Dip plane 2016-2018	Polygons used by the surveyors for draping purposes. Draping is the projection of drawing elements onto a selected pre-set plane.	Excluded in the MOA
Stoping pillars measured 2017-2018	Pillars measured by the surveyor (ground left in the in -situ not mined)	Included in the MOA

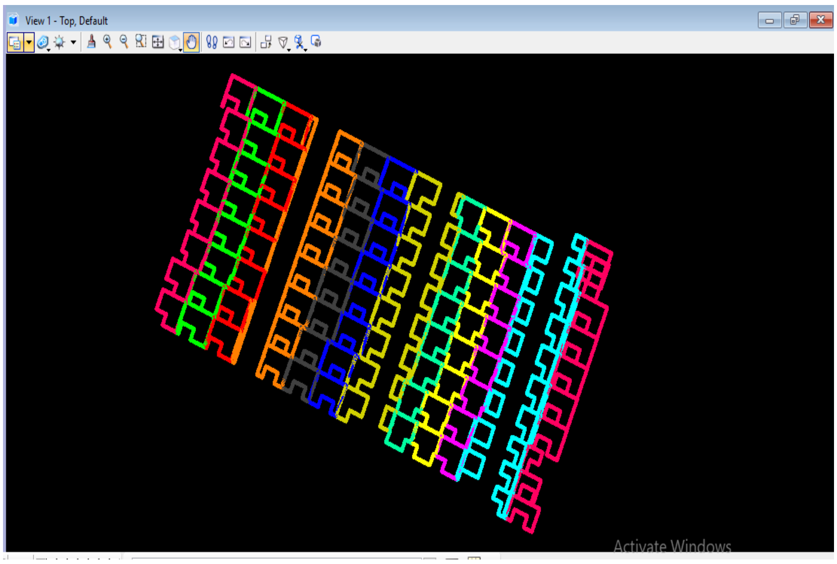
The MOA was further digitized using MicroStation software. Levels were created for each month from January 2018 to December 2018 production year. The result is depicted in the figure below.

Annex A10.3.3: MOA in Microstation



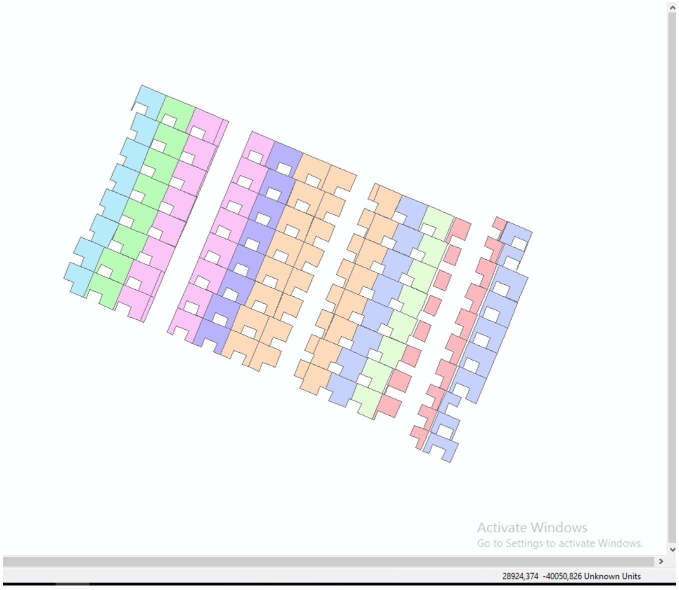
The planned scheduled section for the 2018 production year for Mine A is depicted in the figure below.

Annex A10.3.3: Planned Schedule in MicroStation

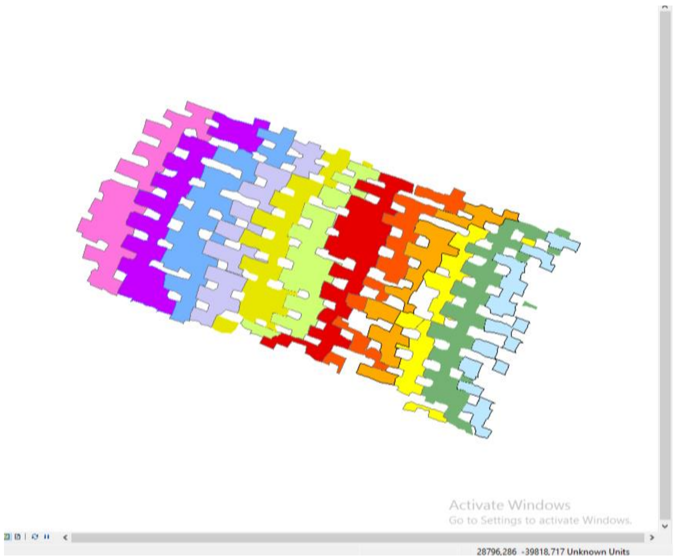


Planned area and actual areas where spatial intelligence for comparing Planned, best cut and actual grade variance maps was conducted in ArcMap are depicted in the figures below.

Annex A10.3.4: Planned production area in 2018 - ArcMap



Annex A10.3.5: Actual production area in 2018



The daily quality and quantity estimates for 2018 Mine A plan, actual, shaft program plan, shaft program actual, planned grade, best-cut grade and actual grade for the section in planned production and actual production aeras above are outlined in Annex A5.

Annex A10.4: Development of grade variance maps for the planned grade, best-cut grade and actual grade.

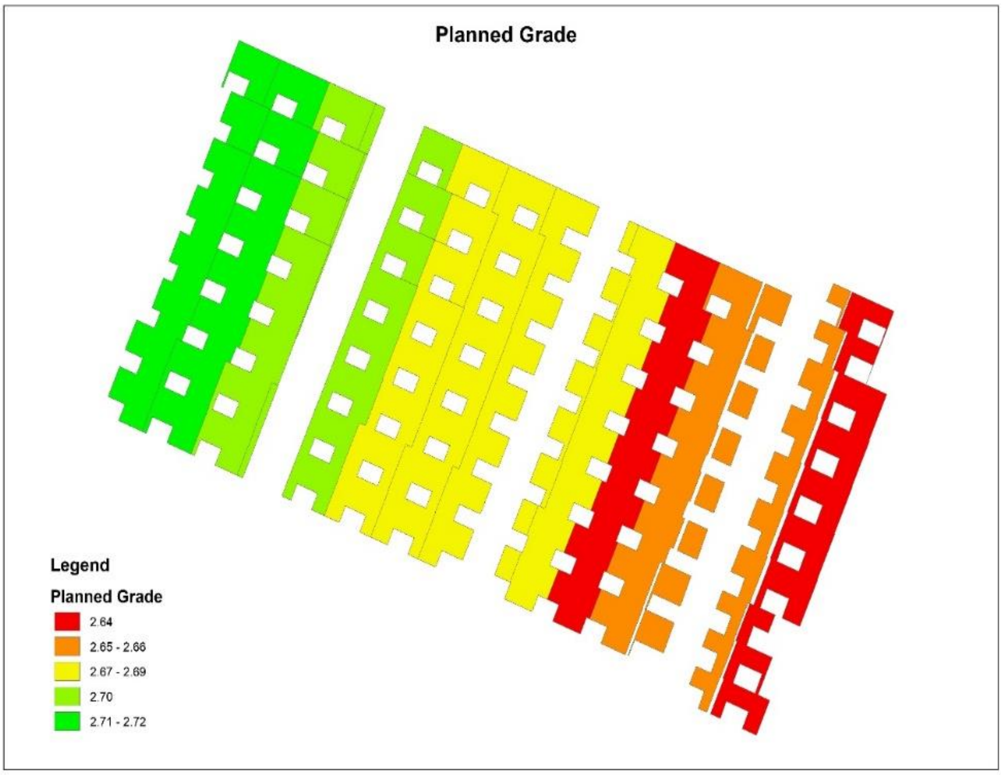
The planned grade, best cut grade, actual grade values are outlined in the table below. The highlighted values in pink are duplicate values and the remaining are not. For example, the planned grade for the month of January and April is 2.64, the planned grade for May, June, and July is 2.69 and the planned grade for the month of September and October is 2.7. The planned grade for the remaining months of February, March, November and December are 2.66, 2.65, 2.71 and 2.72 respectively. These are not duplicate values.

Annex A10.4.1: Planned grade, best-cut grade and actual grade

Date	Planned grade	Best cut grade	Actual grade
01-Jan-18	2,64	2,69	2,69
01-Feb-18	2,66	2,73	2,76
01-Mar-18	2,65	2,73	2,73
01-Apr-18	2,64	2,7	2,64
01-May-18	2,69	2,7	2,61
01-Jun-18	2,69	2,78	2,69
01-Jul-18	2,69	2,78	2,61
01-Aug-18	2,68	2,68	2,64
01-Sep-18	2,7	2,23	1,98
01-Oct-18	2,7	2,64	2,66
01-Nov-18	2,71	2,78	2,73
01-Dec-18	2,72	2,77	2,84
Min	2,64	2,23	1,98
Max	2,72	2,78	2,84

The grades for planned, best cut and actual grades in the table above were used to develop the grade variance maps for planned, best cut and actual grades. The planned grade variance map is depicted below.

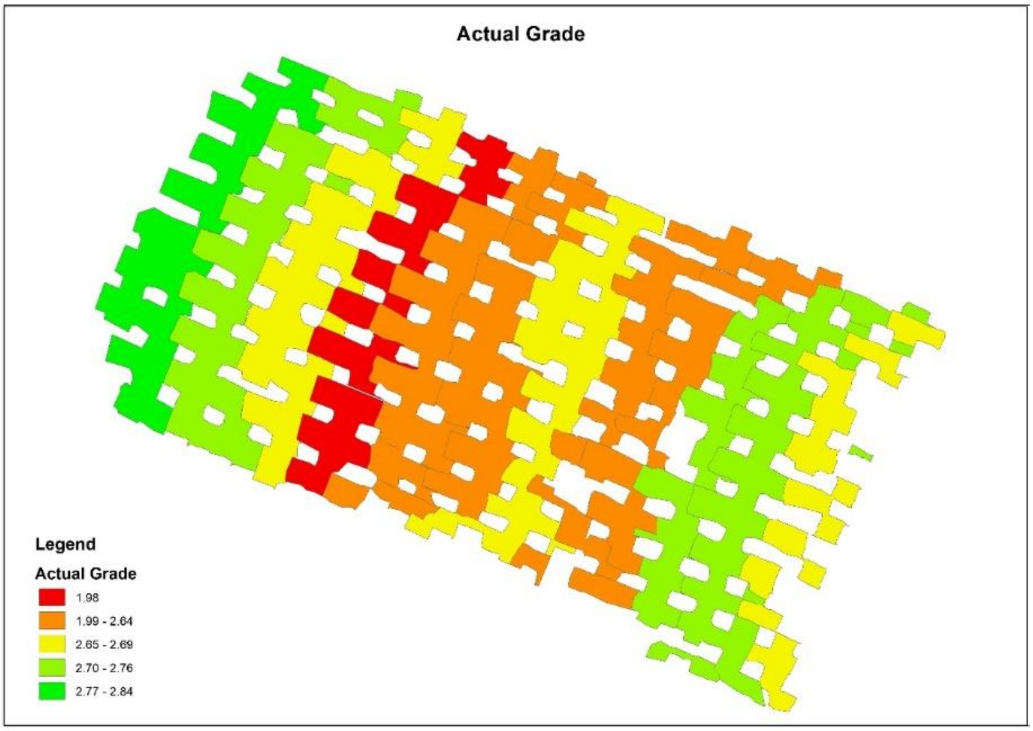
Annex A10.4.2: Planed grade variance map



In the figure above, the minimum grade was 2.64 and the maximum grade is 2.72. The low grade covers a range from 2.64 to 2.66. The medium grade covers a range from 2.67 to 2.69. The maximum grade covers a wide range from 2.70 to 2.72. The grade categories are created using a colour ramp in which the colour red and brown depicts low grade, yellow means medium grade and green means a high grade. The number of classes chosen for the grade variance classification purpose is 5. This process is repeated for the best cut grade, as well as the actual grade variance maps.

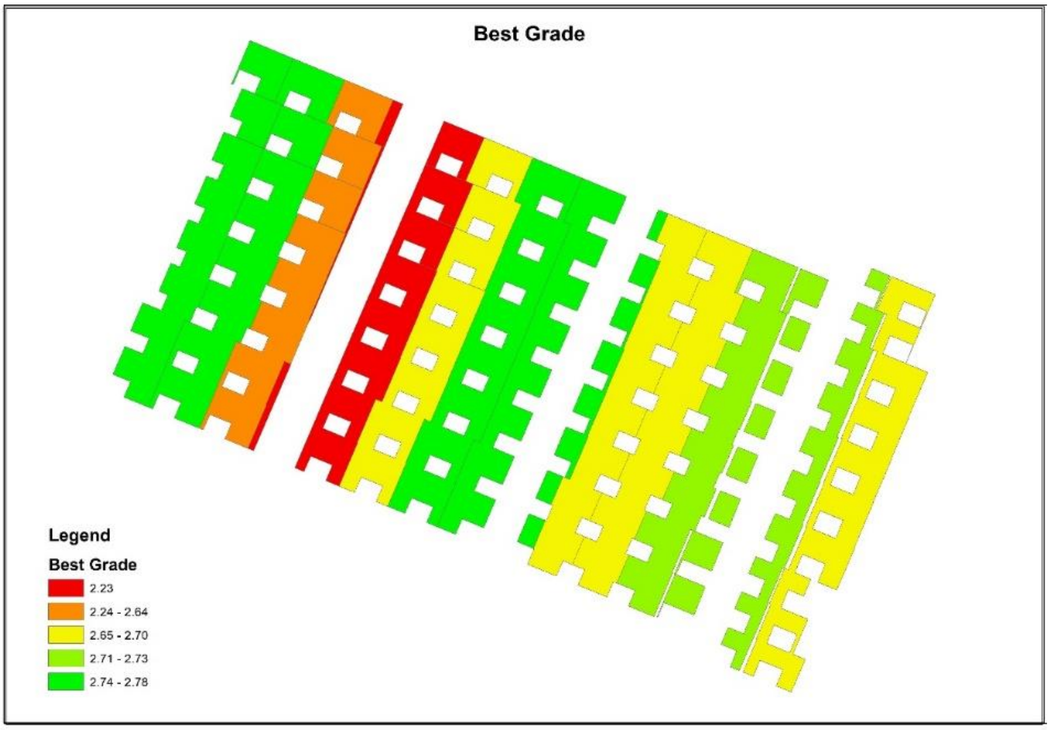
The Figure below depicts the actual grade variance map. The minimum grade is 1.98 and the maximum grade is 2.84. The low grade covers a range from 1.98- to 2.64. The medium-range covers a range from 2.65-2.69 and high grade covers a range from 2.70-2.84. The colour convention for the low-grade, medium grade and high grade is the same as discussed previously.

Annex A10.4.3 Actual grade variance map



The figure below depicts the best cut grade variance map. The minimum grade is 2.23 and the maximum grade is 2.75. The low-grade ranges from 2.23 to 2.64. The medium grade ranges from 2.65 to 2.70. The high-grade ranges from 2.71 – 2.75.

Annex A10.4.4: Best cut grade variance map



The grade variance map enables the determination of how grade varies from the planned, actual and the best cut grade results. The table below gives a monthly interpretation of the grade variance map for the production year 2018.

Annex A10.4.5: Interpretation of grade variance map

Month	Planned grade	Best Cut grade	Actual grade
January	The low grade of 2.64 g/t	Medium grade of 2.68 g/t	The best-cut grade of 2.9 g/t was achieved
February	The low grade of 2.66 g/t	Medium grade of 2.73 g/t	The high grade was achieved in comparison to the best-cut grade and planned grade.
March	The low grade of 2.65 g/t	Medium grade of 2.73 g/t	The best-cut grade of 2.73 g/t was achieved.
April	The low grade of 2.64 g/t	Medium grade of 2.78 g/t	planned grade was achieved
May	The low grade of 2.69 g/t	High grade of 2.78 g/t	Planned and best cut grades was not achieved.
June	Medium grade of 2.69 g/t	A high grade of 2.78 g/t	planned grade was achieved with a medium grade of 2.69g/t.
July	Medium grade of 2.69 g/t	High grade of 2.78 g/t	The medium grade was achieved although was lower than the planned grade
August	Medium grade of 2.68 g/t	Medium grade of 2.68 g/t	The medium grade was achieved although was lower than the planned and best-cut grade.
September	High grade of 2.70 g/t	The low grade of 2.23 g/t	The low grade was achieved and lower than the planned and best-cut grade.
October	High grade of 2.71 g/t	Low-Medium grade of 2.64 g/t	The medium grade was achieved although lower than the planned grade but higher than the best cut grade.
November	High grade of 2.71 g/t	A high grade of 2.78 g/t	Planned grade was achieved, the actual grade is higher than the best cut grade.
December	High grade 2.72 g/t	High grade of 2.77 g/t	Planned and best-cut grades were achieved although the actual grade is higher than planned and best-cut grades.