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BENEFITS OF USING INTERNET OF THINGS TECHNOLOGY FOR FUEL MANAGEMENT AT A MECHANISED UNDERGROUND BORD AND PILLAR PLATINUM MINE: A BATHOPELE MINE CASE STUDY

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2024

DECLARATION

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ABSTRACT

The advent of the fourth industrial revolution, Environmental Social and Governance (ESG), and push for green energy transition has propelled mining companies to reconsider their strategies. Over the past two decades, mining companies along the Bushveld Igneous complex in South Africa have been shifting towards mechanized mining methods which are generally safer and provide for the generation of greater volumes of output. Sibanye Stillwater's Bathopele mine, which has a fleet of over two hundred and fifty (250) trackless mobile machinery (TMM) and a daily fuel consumption of approximately ten thousand (10 000) liters per day. The introduction of Internet of Things (IOT) technology in the fuel management system at Bathopele mine achieved benefits such as fuel consumption tracking, effective inventory management, prevention of fuel theft, detection of fuel leaks, determination of maintenance requirements and readily available access to fuel use data. This access to data enabled the mine to effectively apply for fuel use rebates from the South African Revenue Services (SARS) with ease. To determine the impact of the increased distance to underground working places on the refueling of TMM, the Theory of Constraints (TOC) method, qualitative and quantitative techniques were applied. A bivariate analysis conducted indicated a linear relationship between fuel consumption and production output at Bathopele mine, which suggests that an effective fuel management system had a positive impact on production output at the mine. A real-time or near real time model for fuel management in underground trackless bord and pillar mines in proposed.

DEDICATION

In appreciation of my wife Rethabile Thema and our daughter Lethabo Amisha for their love, patience, and support throughout this journey.

The unwavering support from my parents, Elsie and Chris Thema, for always reminding me of the importance of education and working hard to achieve goals.

Finally, I also dedicate this work to my siblings, Jan, Tlou and Mamoh for always being there for me.

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Sephela Makete “Meneer” Thema

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t	Time in seconds
l	Length in metres
m	Mass in tons
v	Volume in liters
r	Pearson’s coefficient of correlation
R	Currency in rands

LIST OF EQUATIONS

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}$$

Operator safety meeting (OS) + UV checklists (UC) + Tramming time (TT) + Refuelling time (RT) = Total cycle time (TCT)

$y = m\,x + c$

LIST OF ABBREVIATIONS

DPM	Diesel Particulate Matter
DRS	Diesel Refund Scheme
ESG	Environmental Social and Governance
FIR	Fourth Industrial Revolution
FMS	Fuel Management System
IOT	Internet of Things
LHD	Load Haul Dump
OEM	Original Equipment Manufacturer
RAF	Road Accident Fund
RFID	Radio Frequency Identification
SARS	South African Revenue Services
SIC	Short Interval Control
TMM	Trackless Mobile Machinery
TOC	Theory of Constraints
Lube UV	Lubricant and Fuel Utility Vehicle
UV	Utility Vehicle
WEF	World Economic Forum
WSN	Wireless Sensor Network

1. INTRODUCTION

The global mining industry is in transition due to the impact of several change forces. These include the COVID-19 pandemic, Fourth Industrial Revolution (FIR) move towards digitization, increased focus on Environmental Social and Governance (ESG) strategies, green energy transition, rising operating costs and fluctuating commodity prices. According to Deloitte (2022), for mining companies to be sustainable and have a competitive advantage in the future, they must adapt to these changes. The FIR has provided opportunities for several industries to exploit new technologies including the mining sector. The successful application of innovative technologies such as artificial intelligence (AI), machine learning (ML), industrial internet of things (IIOT), virtual reality (VR), drones and autonomous driving has the potential to increase productivity and efficiency and enhance health and safety in harsh mining environments (Gruenhagen & Parker, 2020).

Schwab & Davis (2018) identify the internet of things (IOT) as a fundamental infrastructure element of the FIR. Jacobs & Webber-Youngman (2017) define the IOT as a system consisting of installed sensors and actuators on equipment and physical objects enabling connection to the internet for monitoring data. Zhou et al. (2017) studied the industrial applications of IOT, and one of the major findings of their study was that most of the existing infrastructure (sensors and communication systems) on the mines could be integrated into the industrial IOT systems with little or no modifications. IBM (2024) proposes that as the number of connected IOT devices continues to grow, businesses that are able to adapt and embrace new capabilities and applications will be well positioned to reap the benefits of this transformative technology.

In a market of constant changes, frequent disruptions, volatility, rising stakeholder demands, widening talent gap and diminishing access to energy and water, mining companies must refocus their strategy to realize long term value (Deloitte, 2020). To overcome these challenges, the mining industry must continue finding new ways of doing things. The South African mining sector is also impacted by activities in the global mining market. Deloitte (2014) states that the profit margins of South African mining companies are under pressure due to a combination of falling global commodity prices and rising input costs, which forces them to make difficult decisions to maintain short term operations in line with their long-term objectives.

The Minerals Council of South Africa (2020) , suggest that the shift towards the mechanization and modernization of mines is compulsory, and lists the following as some of the benefits that can be realized; prolonging life of mine, saving jobs, improving safety and health, mining of deeper resources, lower grade orebodies, 24/7 operations and higher skills utilization. The FIR enables mining companies to digitize operations and obtain data containing valuable insights. The World Economic Forum (WEF) white paper on digital transformation, done in collaboration with Accenture, estimates that more than $425 billion value may be realized between years 2015 and 2025 because of digital transformation in the mining industry (WEF, 2017). According to Brzychczy, Gackowiec & Liebetrau (2020) mining companies aim for continuous improvement of their processes to increase operational efficiency and the safety of their personnel.

The shift towards mechanisation in the last two decades in the South African bushveld complex has led to platinum and chrome mines using trackless mobile machinery with diesel powered engines and hydraulic systems underground particularly for shallow and gentle dipping orebodies. Bathopele mine is a mechanised underground platinum mines that uses the bord and pillar mining method. The mine makes use of two hundred and fifty-eight (258) diesel engine-powered trackless mobile machinery (TMM), which is one of the largest fleets of underground equipment at any underground mine in the world, for different operations. Consequently, the consumption of fuel contributes a substantial amount to the operating expenses.

Rayes & Salam (2019) credit the use of IOT for enabling companies to generate new business models, improve business processes, and reduce costs and risks. Likewise, IOT technology applied to existing processes in mining operations offers an array of potential benefits in safety and production. IOT technology has recently been incorporated at the mine in a phased approach to improve the fuel management system. Benefits of the adoption of IOT technology are detailed in the research study, and further options of improving the fuel management system (FMS) at Bathopele mine are explored.

1.1 Problem Statement

Bathopele mine due to its sarge fleet of TMM employed consumes approximately ten thousand (10 000) litres of fuel daily, which made it difficult to manage fuel using traditional methods. To improve the FMS at Bathopele mine, an IOT-based FMS was introduced in 2019. The research report reviews the benefits realized from the shift to IOT-based FMS system, and investigates other opportunities for improving the efficiency of the FMS at Bathopele mine.

1.2 Aims and objectives

The aim of the research study is to illustrate the benefits that may be realized by the introduction of an IOT-based fuel management system at trackless underground bord and pillar mine. The main objective of the research was to determine the benefits of the introduction of an IOT-based fuel management system at Bathopele mine. Additionally, an analytic approach was undertaken to determine ways of improving the fuel management system at Bathopele mine further. The relationship between fuel consumption and production output is investigated to validate the importance of effective fuel management systems. Lastly, a real-time or near real time model for fuel management in underground trackless bord and pillar mines is proposed.

1.3 Factors affecting fuel management system at Bathopele mine

Bathopele is a modern mechanised underground bord and pillar platinum mine that makes use of diesel-powered low-profile equipment such as Load Haul

Dump (LHD) trucks for loading, drill rigs (DR) for face drilling, roof bolters (RB) for support and utility vehicles (UVs) for transportation of men, material, and other logistics. The equipment consumes various amounts of fuel depending on the type of operations are being undertaken. For example, TMM used for the transportation of ore, men and material consume more fuel than TMM used for drilling activities such as roof bolters and drill rigs as they mostly operate from while stationary. The need to improve the efficiency of the fuel management system at Bathopele mine was supported by factors including, large number of TMM in use, mining deeper reserves, contribution of fuel to operating expenses, and the impact of the increasing price of fuel.

1.3.1 Large number of TMM in use at Bathopele mine

Bathopele mine has a large fleet of TMM resulting in large amounts of fuel being consumed during operational activities. A summary of the diesel engine powered TMM fleet from various original equipment manufacturers (OEMs) in use at Bathopele mine is shown in Table 1.

Table 1.1 : Bathopele Mine TMM type summary

TMM type	Quantity	Main Activities
LHD	54	Load Haul Dump
Drill Rig	33	Drilling
Bolters	40	Drilling support holes
PCs	27	Personnel transport
Jeeps	48	Personnel transport
UVs	48	Material Transport
Grader	3	Roadway maintenance
Forklifts	1	Lifting and moving of bulk material
Manitou	2	Lifting and moving of bulk material
LDVs	2	Surface transportation of personnel and goods
Total number of TMM	258	

The main activities that are undertaken by each type of TMM has a direct influence on the fuel consumption, and thus TMM that are used for activities that involve regular travelling (LHDs, personnel carriers and utility vehicles) consume more fuel than TMM that are utilized mainly from a stationary position (Drill Rigs and Bolters). It is important to have a fuel management system in order ensure that adequate reserves of fuel are kept on site while ensuring that there is enough to keep TMM operating. The management of fuel includes the storage, transportation, consumption, and record-keeping of all activities in the refuelling cycle. Analysis of the breakdown history of primary TMM at Bathopele mine over six months (January to June 2021), shown in Figure 1.1, indicates sixty three percent (63%) of fuel related downtimes for LHDs, and the remaining thirty-seven percent (37%) for both Boltecs and Drill Rigs. This indicates the the critical role fuel management plays at mechanised mining operations.

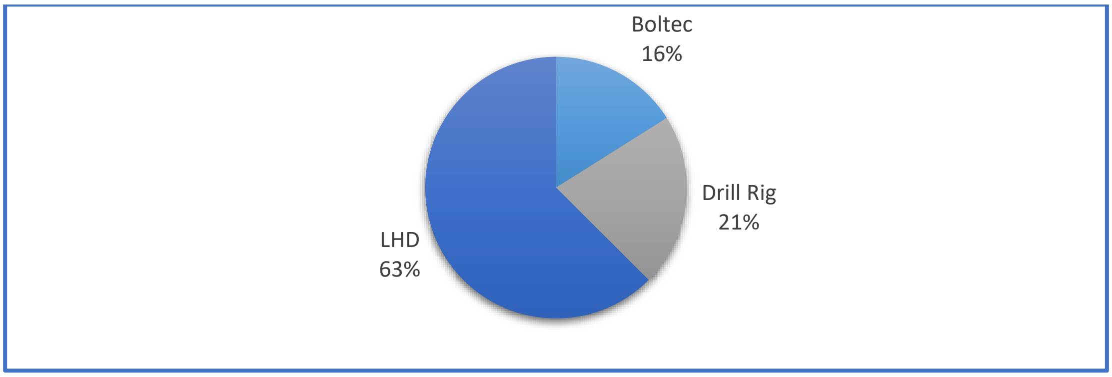

Figure 1.1: Fuel-related breakdowns reported over a period of six months

1.3.2 Mining deeper reserves

Depleting ore reserves and lower ore grades compel mining companies to turn to deeper-lying new deposits (Jacobs & Webber-Youngman, 2017). As mining progresses, the distance from the mine shaft and fixed infrastructure increases and hence the distance travelled to reach the working places as increases. This results in the time taken to transport men, material and other resources to the workplaces also increasing. The increasing depth of mining may lead to production inefficiencies, unsafe conditions and an unhealthy work environment (Minerals Council of South Africa, 2020). For underground trackless mining operations like Bathopele, workplaces advance with every blast moving away from the shaft infrastructure and increase distance to working places. The time it takes to refill primary TMM also increases. The increasing refuelling cycle time has the effect of prolonging downtimes of primary production equipment due to the lack of fuel and/or lubricants.

1.3.3 Contribution to operating expenses

Fuel costs contribute significantly to the operating expenses at Bathopele mine. According to Pricewaterhousecoopers (2018), the South African mining industry's operating expenses grew by eight percent (8%) from year 2018 and 2019. It is important for each mine to identify its main cost drivers and find creative ways of minimising them. The average cost breakdown contribution for engineering and equipment at Bathopele mine for year 2019 is shown in Figure 1.2.

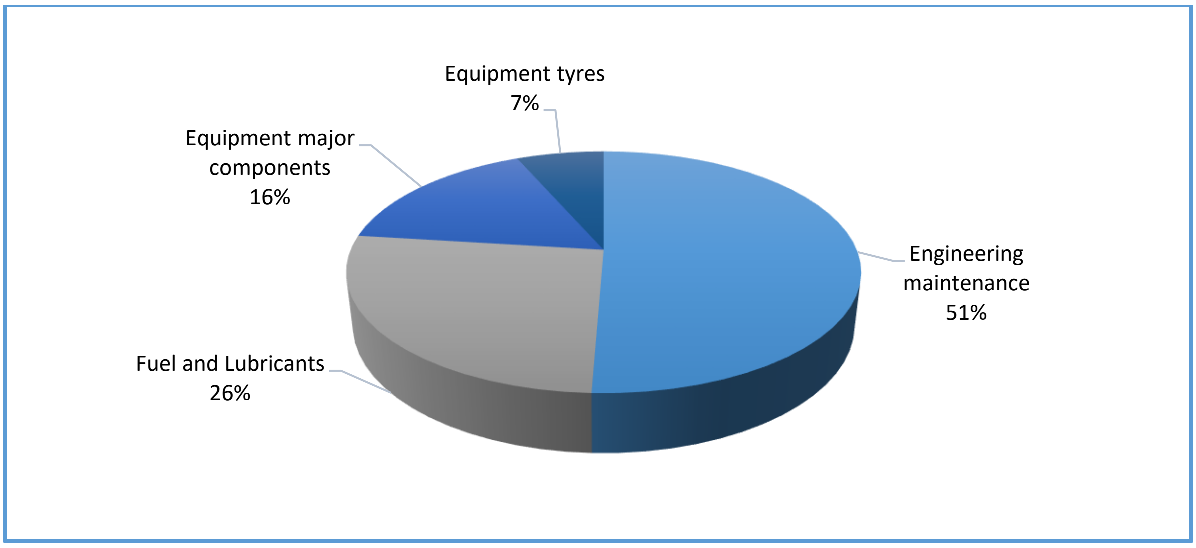

Figure 1.2: Engineering and equipment average monthly expenses at Bathopele mine for 2019

Engineering maintenance costs contributed to fifty one percent (51%) as they included an array of cost components including costs of original equipment manufacturer managed equipment, maintenance parts, capital on new equipment, and wear and tear repairs. The expense attributable to the consumption of fuel and lubricants contribute 26% of the total engineering and equipment costs on average.

1.3.4 Impact of increasing fuel costs

Generally fuel prices in South Africa have doubled between the years 2007 and 2017, and mainly due to local currency exchanges and global oil prices (Businesstech, 2018). The upward increase in diesel prices, shown in Figure 1.3, has had a significant impact on the operational costs of surface and mechanised underground trackless mines. The price of diesel has increased by one hundred percent between year 2007 and 2017.

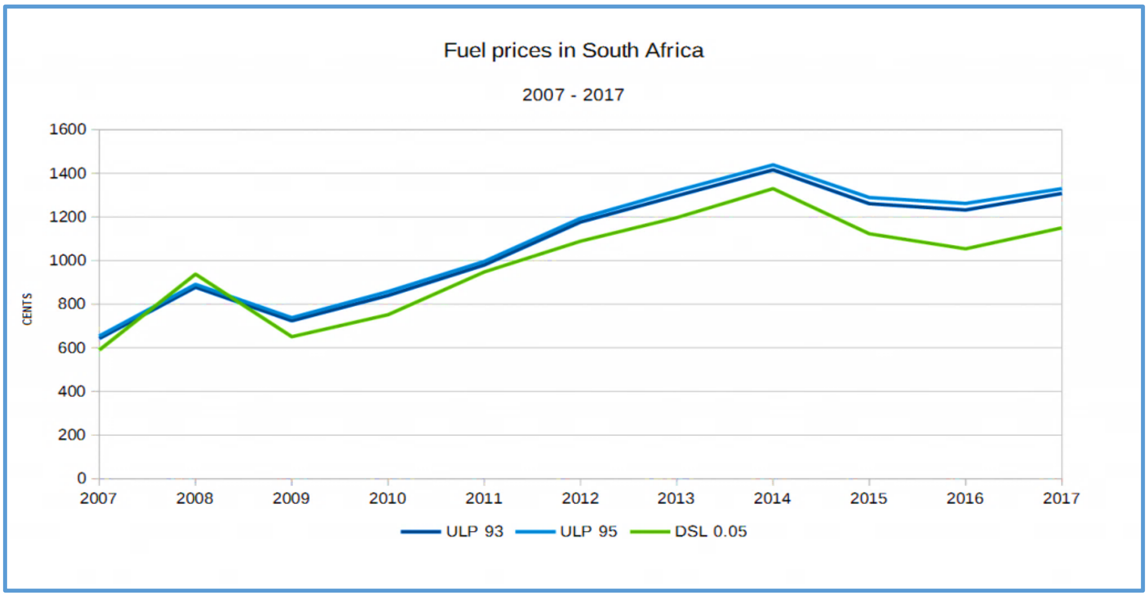

Figure 1.3: Ten-year fuel prices history in South Africa (Businesstech, 2018)

The mining sector is still very reliant of diesel powered trucks for surface and TMM for underground mining. Keen et al. (2022) state that most open pit copper mines make use of truck fleets that use fossil fuels scuh as diesel. As an after effect of the Covid-19 pandemic and lowered economic production activity, the prices of fuel have spiked after year 2020 as indicated in Figure 1.4.

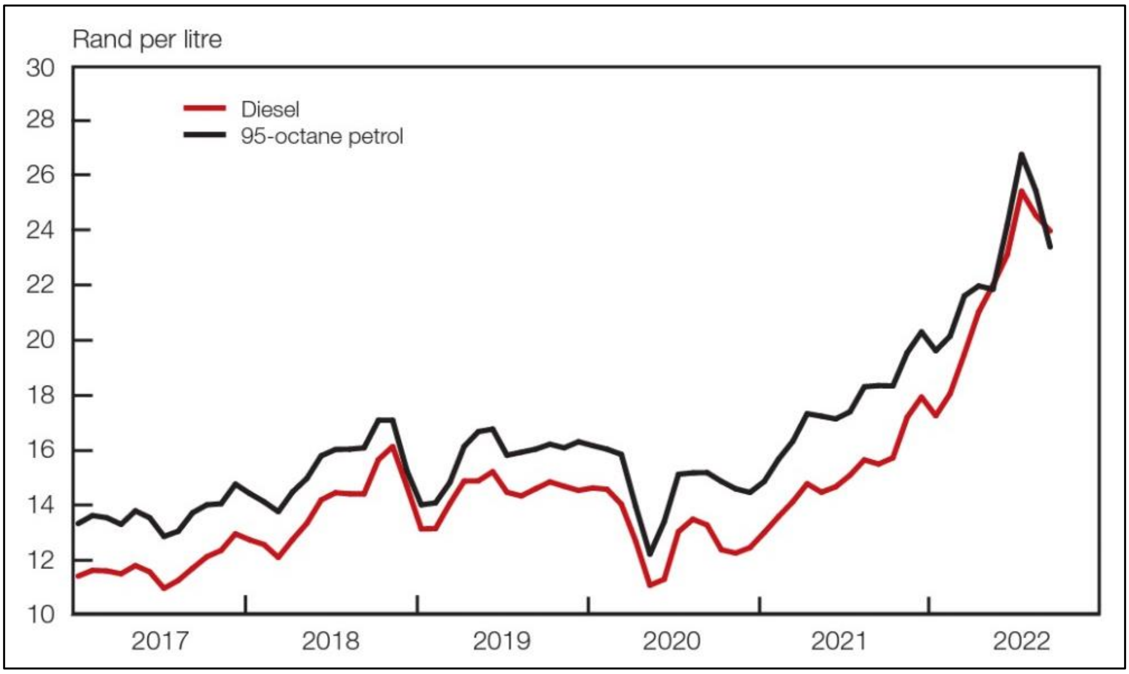

Figure 1.4: Five-year fuel history in South Africa (Businesstech, 2022)

In Figure 1.5, the increasing share of energy in copper mining costs is shown by the line graph indicating a steady increase from year 2016 to date. South African platinum miners are heavily exposed to rising energy prices, and with rise in commodity prices lagging, they have less ability to absorb higher costs (Keen *et al.*, 2022).

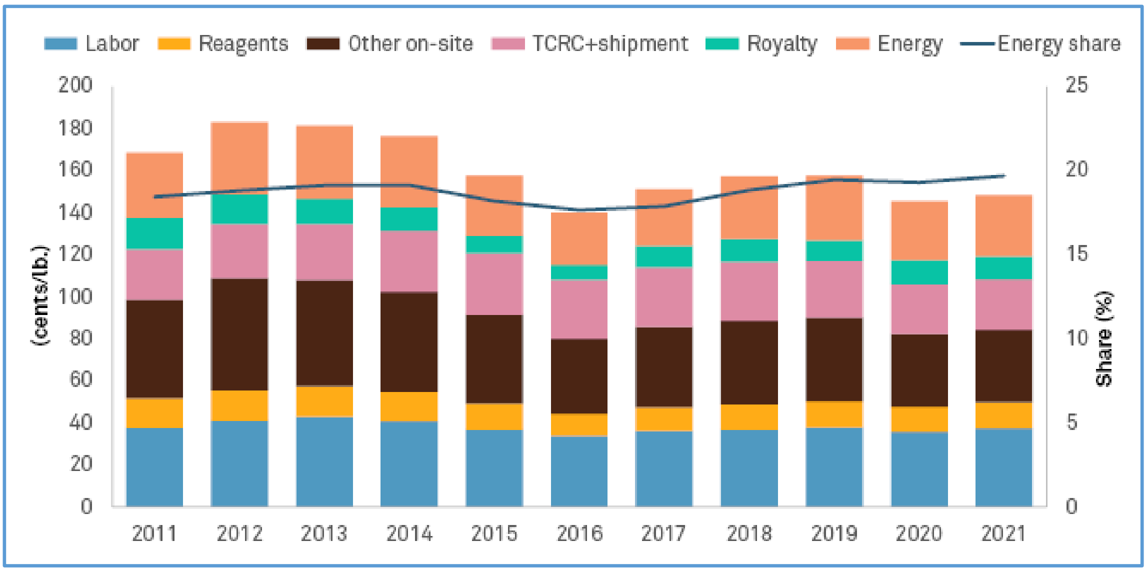

Figure 1.5: Share of energy in copper mining costs (Keen et al.*, 2022)*

1.4 Justification for Research

Fuel management is traditionally a research topic for surface mines due to the high fuel consumption of diesel-engine powered surface mining trucks travelling to and from the pit to surface with a heavy payload. However, in the last two decades a migration towards mechanization has resulted in several mines using large fleets of diesel-engine powered TMM underground. Mechanized mining methods offered the benefits of immediate access to the orebody, rapid production build up and improved labour productivity (Egerton, 2004). The increasing depth of mining due to advancing workplaces and deeper lying reserves at Bathopele mine has necessitated the need to investigate options for improving the fuel management system.

The emergence of IOT technology has provided an array of possible solutions for industries such as mining where the data from operations can be harnessed to solve problems encountered. There have been several case studies in the mining sector at organizations including Sibanye Stillwater, Goldcorp, Metso and Schneider Electric that have shown the value addition of using IOT technology in operations. In the case of Bathopele mine, the use IOT technology has not only exposed several opportunities for optimization of the fuel management system, but also brought to light constraints in the fuel management flow.

1.4.1 Fuel management in underground mines

The adoption of mechanisation in the last two decades in the South African Bushveld Complex has led to platinum and chrome mines using trackless mobile machinery with diesel-powered engines and hydraulic systems underground. This has increased the consumption of fuel as well as the requirement of good fuel management systems. Management of fuel in underground trackless mines has not been extensively researched. Lack of operational visibility and limited communication infrastructure is more of a challenge in underground than surface mines (Ferreira, 2017). Therefore, is a need to find research-based solutions to improve the management of fuel in underground trackless mining operations. Song et al. (2013) states that the application of process control concepts is more complex in underground mines than surface mines which use existing wireless and Global Positioning Systems (GPS) infrastructure.

1.4.2 Internet of things capabilities

The increasing adoption of IOT technologies in the mining industry has seen several successful case studies. The implementation of IOT technologies has enabled mines to harness the data generated to realize a variety of objectives successfully. Using digital technologies simultaneously to manage operating systems increases their capabilities as shown in Figure 1.6.

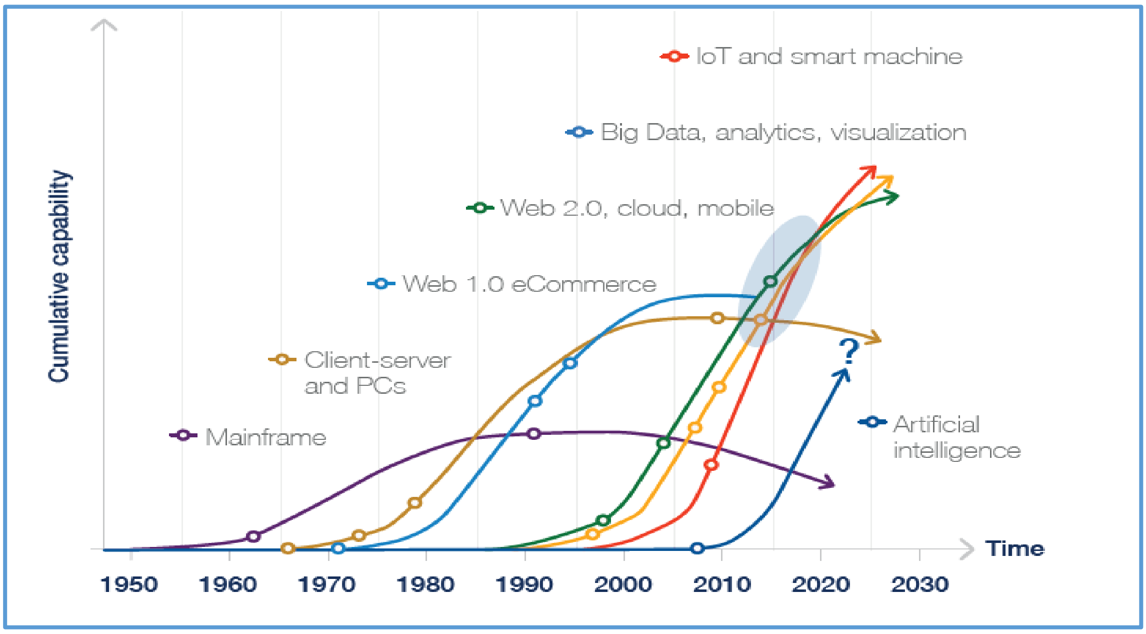

Figure 1.6 - Increasing capability of digital technologies (WEF, 2017)

The IOT and smart machines have accumulated the greatest capabilities in the past five (5) years, however for the purposes of this research is on the former. The findings of this research study will add to the growing list of IOT application case studies in mining. Various case studies have demonstrated the benefits of using IOT for different applications at Sibanye Stillwater, Goldcorp, Metso, and Schneider Electric:

Sibanye Stillwater Bathopele mine underground clocking system has installed sensors on the turnstiles for underground clocking, which detect the required safety equipment that employees take underground and denies employees access if they do not have safety equipment with them or the equipment was not tested. Safety equipment like self-contained self-rescuers, cap lamps and gas detection instruments for mining supervisors. The system ensures that, firstly all employees clocking for underground have their safety equipment, and secondly the equipment has been tested and is in working condition.

"*Goldcorp a gold producer headquartered in Canada, is using smart sensors in its Éléonore Mine*. *Management has deployed a network of sensors and monitors to ensure the safety and efficiency of workers and equipment. Using the tracking system, the company can ensure that workers are clear during planned blasting work and manage the mine's air filtration system by sending fresh air to the areas that need it most. Prioritisation of the air filtration system has delivered a 50% reduction in the amount of air required to service the mine."* (WEF, 2017)

"Metso visual sensors enable clients to monitor the bubbles in their steel production which resulted in a higher quality and consistent product." (WEF, 2017)

> **Schneider Electric’s Integrated Planning and Optimization Solution (IPOS)** is designed to optimize supply chain efficiency for mining companies. The IPOS solution has the potential to boost productivity by up to 20% through optimizing the resource-to-market chain’ (WEF, 2017)

Yinghua et al. (2012, p. 5) conducted a study to improve the safety supervision of a coal mine in China, and they arrived at the conclusion that ”*Through adopting IOT technology for remote dynamic supervision, coal mine supervising pattern can be innovated, tracking inspection on illegal action can be achieved, capabilities of emergency response and accident investigation can be increased, situation of safe production can be further improved, and safe and stable development of coal industry can be promoted*.” IOT technology has the capability of improving safety and production in the mining sector when applied in various systems and operational activities.

1.5 Purpose of the Study

The purpose of this study is to demonstrate the benefits realised by using the internet of things technology for fuel management at Bathopele mine. The study also explores other opportunities available for the optimization of production activities and efficient fuel use from the studies and observations conducted. Findings in this research study will be used for the formulation of a near real-time or real time model for fuel management in mechanised underground bord and pillar mines.

1.5 Structure of the Dissertation

The research study has been divided into seven main sections, and the chapter outline is as follows:

Chapter 1: Introduction – Of the topic of research, problem statement, aims and objectives, research background, justification and purpose of the research.

Chapter 2: Review of Literature – Internet of Things – Review of the literature on internet of things. Requirements and challenges of the use of IOT, applications in mining and benefits are discussed.

Chapter 3: Research Methodology – Illustrates research methods, tools and data analysis techniques, assumptions and limitations of the dissertation.

Chapter 4: Provides an overview of Bathopele mine and the bord and pillar mining method. Discusses the FMS, refueling cycle and application of TOC to the refueling cycle at Bathopele mine.

Chapter 5: Benefits of Using IOT Technology for fuel management at Bathopele mine. The use of data and a model for near real-time or real time FMS for mechanized bord and pillar mines.

Chapter 6: Conclusion and Recommendations – A summary of key findings and recommendations of the dissertation.

Chapter 7: Reference List – list of sources cited in the dissertation.

2. REVIEW OF LITERATURE: INTERNET OF THINGS (IOT)

In this chapter, a literature review of the concept of IOT and the different types of associated technology applications are defined. The infrastructure requirements for the operation of IOT technology systems, challenges and security requirements are discussed. The application of IOT in mining and associated benefits, and process control enablement are also discussed.

2.1 The Definition of IOT

The IOT is an emerging technology platform comprised of a universal network of machines and devices which can interact with each other. IOT applications make device-to-device and human-to-device interaction possible in a reliable and robust form (Lee & Lee, 2015). A more detailed definition includes the standards and process that govern the operations of IOT. This definition was proposed by Rayes & Salam (2019), and it states that IOT is defined as: "*Standards" and "Processes" allowing "Things" to be connected over the "Internet" to exchange "Data" using industry "Standards" that guarantee interoperability and enabling useful and mostly automated* ". Therefore, the IOT is made up of mainly four components namely, Internet, data, processes and standards, and things which operate in a system to provide insights into operational activities. According to IBM (2024), the growing number of internet-connected devices will ensure that IOT plays an increasingly integral role in shaping our world, changing the way of life and how people communicate with each other. The internet of things refers to the use of embedded sensors and actuators in machines and other physical objects that connect them to the internet (Jacobs & Webber-Youngman, 2017). The internet makes it possible to connect the sensors (things), through processors to generate data, as shown in figure 2.1.

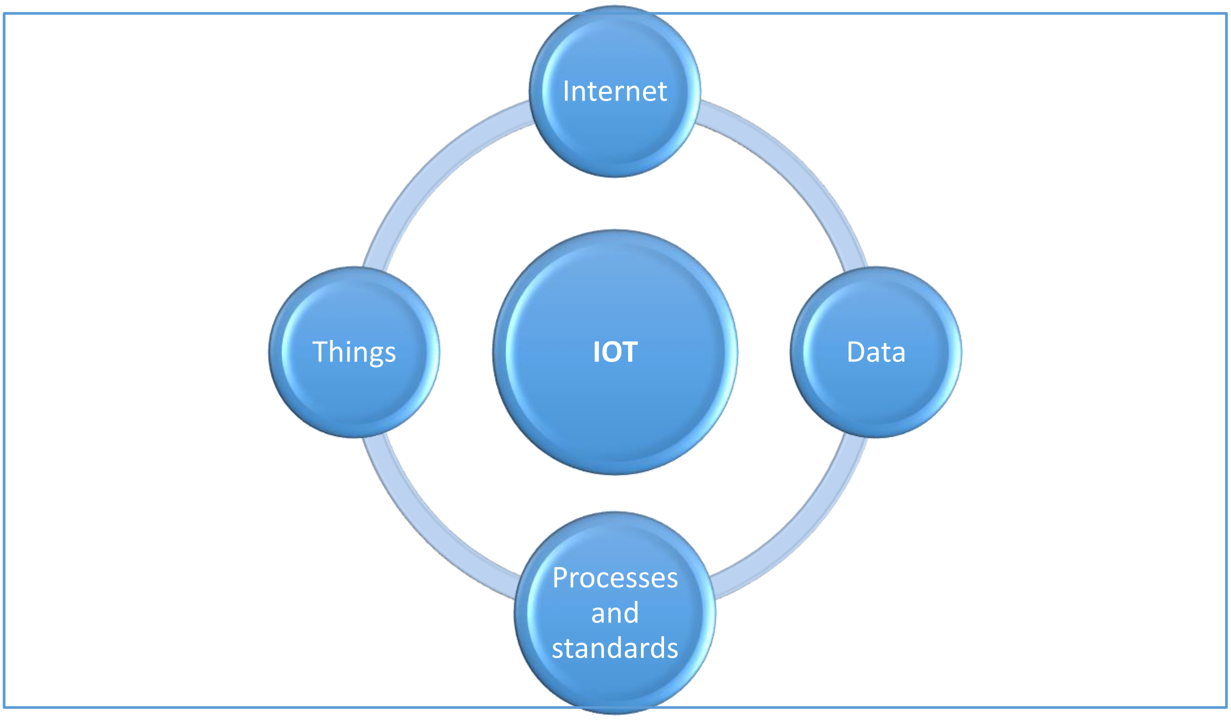

Figure 2.1: The definition of IOT (Rayes & Salam, 2019)

According to Zhou et al. (2017), the primary end-users of the industrial IOT are command centres. The secondary users of data are the managers, operators, engineers, and anybody interested in deriving insights from the system. The main function of IOT involves the collection and analysis of large amounts of structured and unstructured data from various internal and external sources, like social media, with the aim of offering better services and improving business processes to gain competitive advantage (Rayes & Salam, 2019). IOT devices (things) can be analyzed in real time to monitor performance, identify patterns and trends which can be used to assist companies to optimize operations and improve their profit (IBM, 2024).

Schwab & Davis (2018, p.98) suggest that ”*as business models take advantage of the internet of things (IOT) to optimise their operations and create a ’pull economy‘, the world around us will continuously anticipate our needs by analysing our patterns of behaviour*.“ Therefore, the interpretation for the research study is that the ‘pull economy’ resembles the operating environment, and the ‘world’ resembles the command centre or control room, which must anticipate the fuel and lubrication requirements of production equipment.

2.2 Types of IOT Technologies

There are several technologies that are complementary in the use of IOT. Lee & Lee (2015) list five commonly used IOT technologies in the application of IOT-based projects. These technologies include radio frequency identification (RFID), wireless sensor networks (WSN), middleware, cloud computing, and IOT application software as shown in Figure2.2.

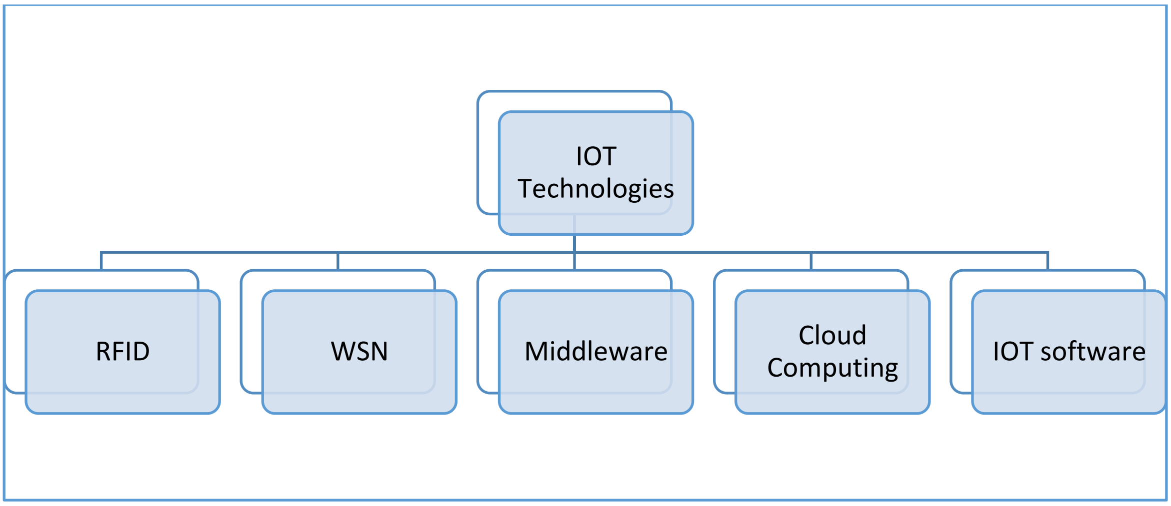

Figure 2.2: Commonly used IOT Technologies (Lee & Lee, 2015)

RFID enables automatic identification and data capture using radio waves through a tag and a reader, and WSN comprises of strategically distributed sensor-equipped devices to monitor prevailing physical or environmental conditions (Lee & Lee, 2015). According to Rayes & Salam (2019) middleware refers to a layer that is placed between applications and underlying network services. The large amount of data generated by IOT technologies may necessitate the requirements for additional storage capacity. Cloud computing offers companies the option of outsourcing their computing infrastructure partially or fully to cloud providers (Rayes & Salam, 2019). Different combinations of IOT technologies are used depending on the objectives and desired outcomes of such projects. The IOT-based fuel management system at Bathopele mine comprises of RFID (tags), WSN, Middleware, Cloud computing capabilities and IOT software.

2.3 Infrastructure Requirements of IOT Technology

There are four basic requirements for the operation of an IOT network. According to Rayes & Salam (2019) for an IOT system to function it needs a unique identity per thing, the ability to communicate between things, the ability to sense specific information, and the medium to communicate. These requirements are shown in Figure 2.3, which also shows examples of the IOT tools that fulfil each requirement.

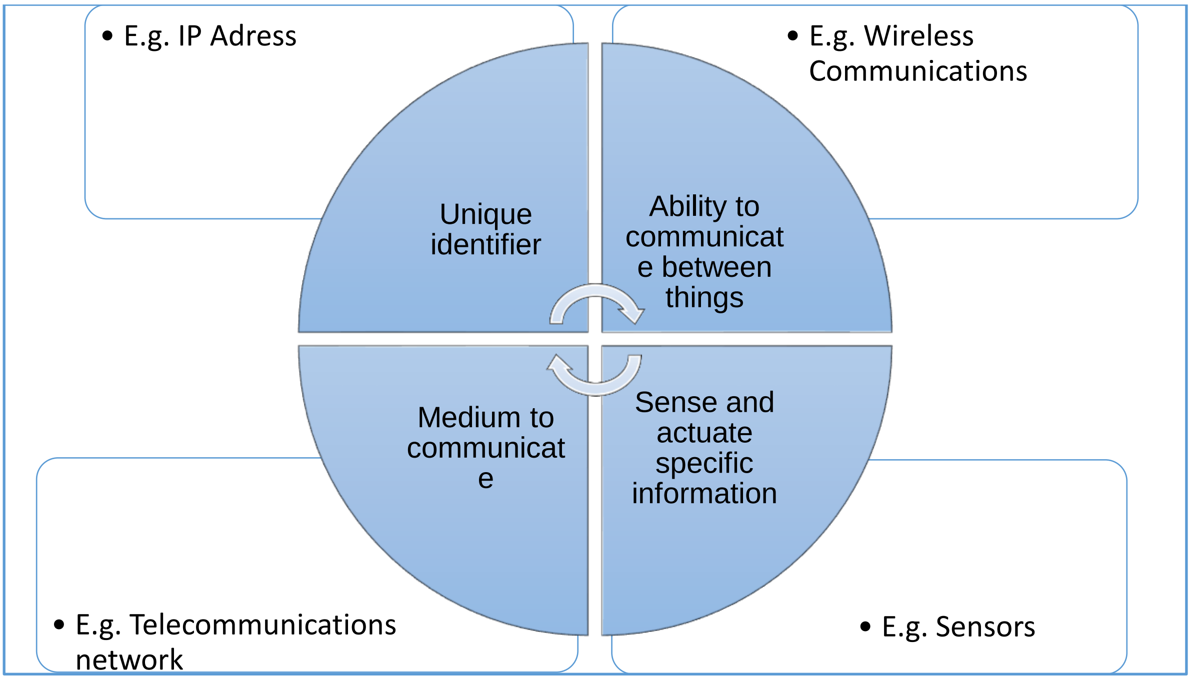

Figure 2.3 - Basic requirements of IOT (Rayes & Salam, 2019)

Rayes & Salam (2019) propose a four-level approach four categorizing IOT solutions as shown in figure 16. Level four (4) IOT applications include solutions such as customer relationships management, while level three (3) is concerned with software for managing IOT services. Level two (2) includes IOT solutions such as the network infrastructure, and level one (1) solutions involve IOT devices or things. Control is transferred from one level to the next as shown in Figure 2.4 below.

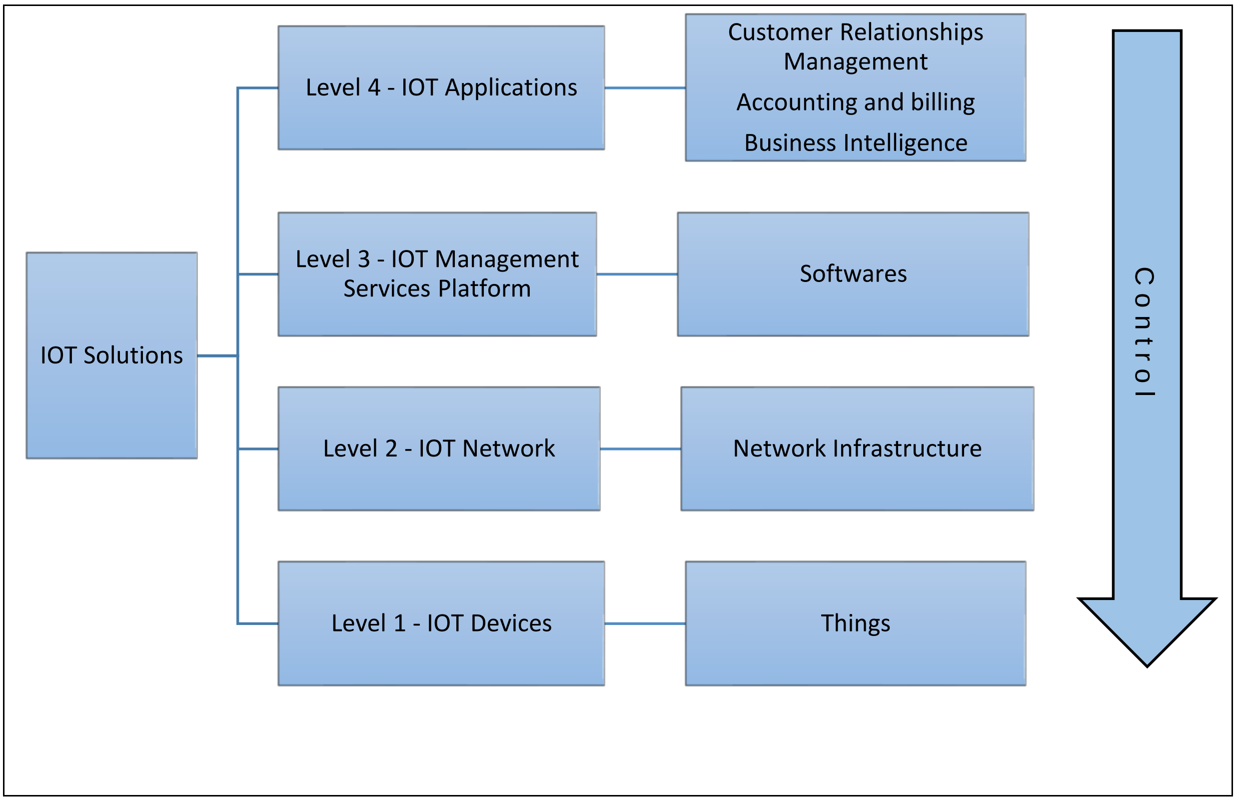

Figure 7 - IOT solutions levels (Rayes & Salam, 2019)

The research study focuses on level four of IOT applications where business insights are derived from the system through partnership with service providers of the IOT technology at Bathopele mine.

2.4 IOT Challenges and Security Requirements

As with most technology systems, the challenge with the application of IOT is in the implementation phase which often requires buy-in of the stakeholders, changes to operating systems, financial investment and training of personnel who will be interacting with the new system. According to Lee & Lee (2015), there are five challenges identified in the adoption of IOT technologies by enterprises:

- The first challenge is data management, which relates to the ability of the system to control large amounts of data.
- Secondly, data mining poses the challenge of data centres requiring the ability to apply corrective processes to address operational issues.
- The third challenge is to maintain the privacy of the data generated.
- Safeguarding of the IOT system against hackers and cybercriminals is the fourth challenge.
- Lastly, the challenge of managing the risk of multi-purpose devices and collaborative applications descending into chaos. Security requirements are one of the main issues that need to be addressed when implementing IOT systems.

Rayes & Salam (2019) summarise the IOT security requirement aspects into nine categories:

- Confidentiality

- Integrity
- Authentication
- Availability
- Authorisation
- Freshness
- Nonrepudiation
- Forward secrecy, and
- Backward secrecy

Confidentiality allows only intended recipients to have access to data. Integrity secures data to ensure that it was not interfered with by third parties. Authentication ensures that the entities involved are verified. Availability prevents the interruption of services. Authorization allows only authorized entities access to system functions. Freshness maintains original data by preventing replay attacks. Non-repudiation prevents entities from denying the history of their actions. Forward Secrecy is for ensuring that after leaving the network, objects will not understand subsequent communications exchanged. Backward Secrecy ensures that a new object joining the network is unable to understand communications preceding their entry.

2.5 Applications of IOT in Mining

Zhou et al. (2017) credit the advancements in sensing technology for the use of sensors in underground mines to measure critical operational and environmental parameters like carbon monoxide concentration, methane concentration, airflow, temperature, and belt running conditions. Mining companies generate large amounts of data, but few use it to obtain value (Goodman, Rajagopaul & Cassim, 2019). In certain instances, it has been established that miners use less than 1 per cent of the data they generate (Schneider-Electric, 2018). According to (Ferreira, 2017) the lack of operational visibility and reliable data capture may result in poor decision-making and an inefficient production process.

Schwab & Davis (2018) outline the three main capabilities of IOT. The first involves data combination with smart analytics, which allows systems to produce new sources of contextual data to reflect activities in the wider environment. Secondly, communication and coordination of devices with great potential to enhance efficiency and productivity. Thirdly, the provision of intelligent-interactive objects that provide new channels for delivering value to clients. The sensors and connectivity capabilities of IOT make underground hazards visible to both surface and underground miners (Zhou et al., 2017). The primary function of IOT applications is to ensure that data generated is received and acted upon in a timely manner (Lee & Lee, 2015). IOT technology enables mine management to use the data gathered by the sensors and generated by the IOT system to make decisions based on the data available to them. The effective management of fuel has been researched and applied on surface mining operations due to the extensive and historical use of diesel-powered trackless mining equipment.

2.5.1 The benefits of IOT for mining

Kent (2017) suggests that the need for innovative solutions propels underground mines to modernize their processes and will promote awareness of the important role of communication platforms in the underground environment. The FIR has transformed the data handling capacity of networks and storage systems with the ability to handle and process large volumes of data, and to analyze and report data in valuable form (Kent and Eisner, 2015). A typical IOT layout for mining is shown in Figure 2.5.

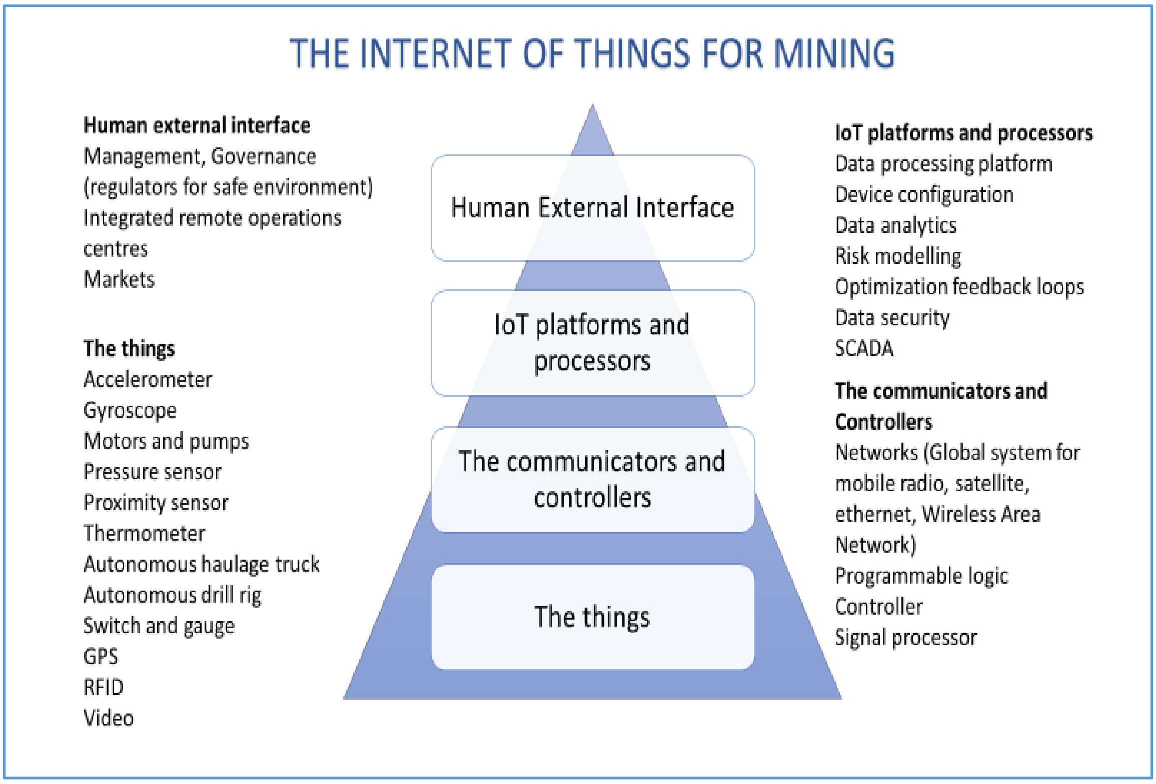

Figure 8: IOT layout for mining (Kent & Eisner (2015)

There are several benefits that can be derived from the application of IOT in mining operations. Zhou et al. (2017), suggests that the application of the industrial IOT can reduce or eliminate hazard exposure, forecast potential disasters, enable the automation of mining equipment, promote energy optimisation, post-accident rescue coordination, accident investigation and smart refuge alternative systems. However, prevailing operational factors and environmental conditions in mining give rise to the challenge of applying IOT technologies. Mine operational environment factors such as moisture, dust, temperature, vibrations, and others have the potential to influence sensor readings (Brzychczy, Gackowiec & Liebetrau, 2020). According to Zhou et al.

(2017), environmental conditions such as extreme moisture, dust, gas concentrations, and potentially explosive underground atmosphere need to be considered for IOT technologies implementation underground. Operational factors such as confined spaces, mining layout and tunnel-like structures must also be considered (Zhou et al., 2017).

According to (Kent, 2017) technologies such as IOT can support different business applications with competencies such as short-interval control, connecting devices, remote mining and automation systems, paperless reporting, monitoring, and managing underground activities. Short-interval control which refers to the proactive management of mining tasks by analyzing adequate reliable data, and reporting deviations in a timely manner. Issues arising during the shift can be quickly detected and corrected through short interval control to reduce the potential loss of production (Song et al., 2013). Connecting devices to build a solid network with the capabilities of harnessing data through IOT and deriving insights from business analytics, remote mining and automation systems allowing for the withdrawal of the worker from the mining face (Kent, 2017). Using multiservice IP networks to implement the automation application, and paperless reporting which refers to the use of digital devices in a connected environment supplying information to a database for recording (Kent, 2017). The increasing demands for monitoring, analyzing and managing underground activities through data generated has increased the requirement for high bandwidth networks underground (Kent, 2017).

Ferreira (2017) proposes that due to the lack of operational visibility in underground mining, it is important to implement a fleet management system which can determine the location, activities, and performance of mobile equipment. An efficient communication system is required for the mine manage activities and detect delays or interruptions to the production process during the shift (Song et al., 2013).

2.5.2 Using process control for mining.

Song et al. (2013) proposes the use of process control for mining, which refers to the automatic control of the output of a process according to objectives set by adjusting input variables based on the model being used. According to (Brzychczy, Gackowiec & Liebetrau, 2020) data pre-processing is required to identify and exclude outliers and abnormal behaviour to use data for the identification of process steps or machine conditions. Ferreira (2017) states that an underground fleet management system can improve efficiency, equipment utilisation, reporting accuracy, use of automated task management, location, status tracking and real time data capture. A generic approach to process control mining implementation is depicted in Figure 2.6. Sensors in the operating environment harness raw data though a data processing platform (i.e. pre processing, activity definition and event log creation) and produce an input for process mining.

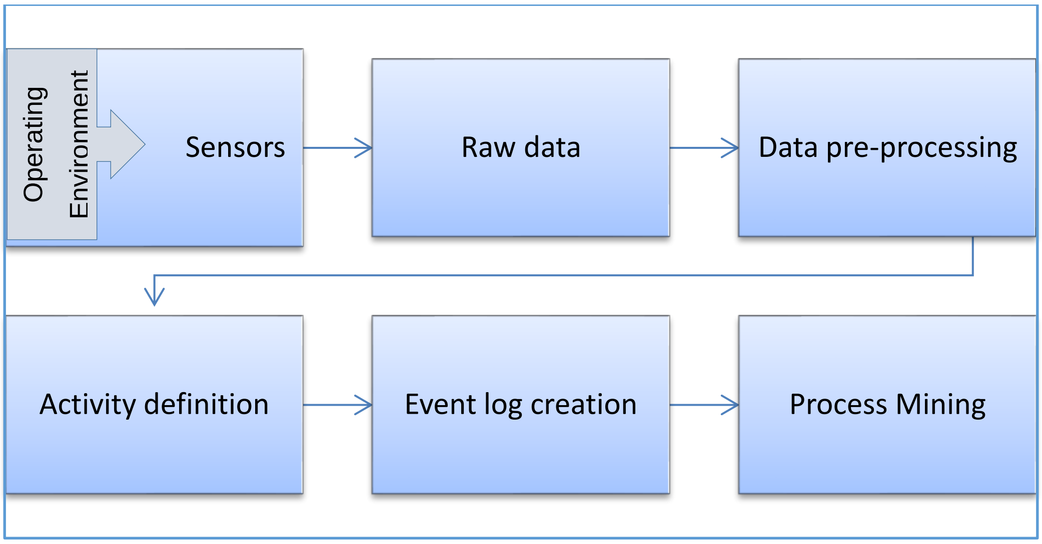

Figure 9: General approach to mining process control implementation (Brzychczy, Gackowiec & Liebetrau (2020)

The data must be attributed to a particular process and analysed accordingly to provide for thorough efficiency and safety analysis (Brzychczy, Gackowiec & Liebetrau, 2020). IOT technology enables miners to use the data gathered by the sensors and generated by the IOT system. The sensors and connectivity capabilities of IOT make operational hazards visible in both surface and underground miners. (Zhou et al., 2017). Song et al. (2013) suggests that for underground mines to employ process control, they need to invest in cable-based communication and positioning systems.

2.6 Using Internet of Things: A Cognitive Approach to Fuel Management

The general principles of fuel management for surface and underground mining have a similar objective, which is to monitor the inventory levels, supply fuel and lubricants, track consumption, and identify problem areas in order maximize the availability of equipment. According to Song et al. (2013) process control systems for underground mining are not as advanced as for surface mining, this is due to the complexity of the excavation and dynamic production phases of underground mines. Tata (2018) propose a cognitive approach for fuel optimisation, shown in Figure 2.7, which involves the use of Internet of things and cloud technology through a command centre to give a real-time view into operations and decisions support.

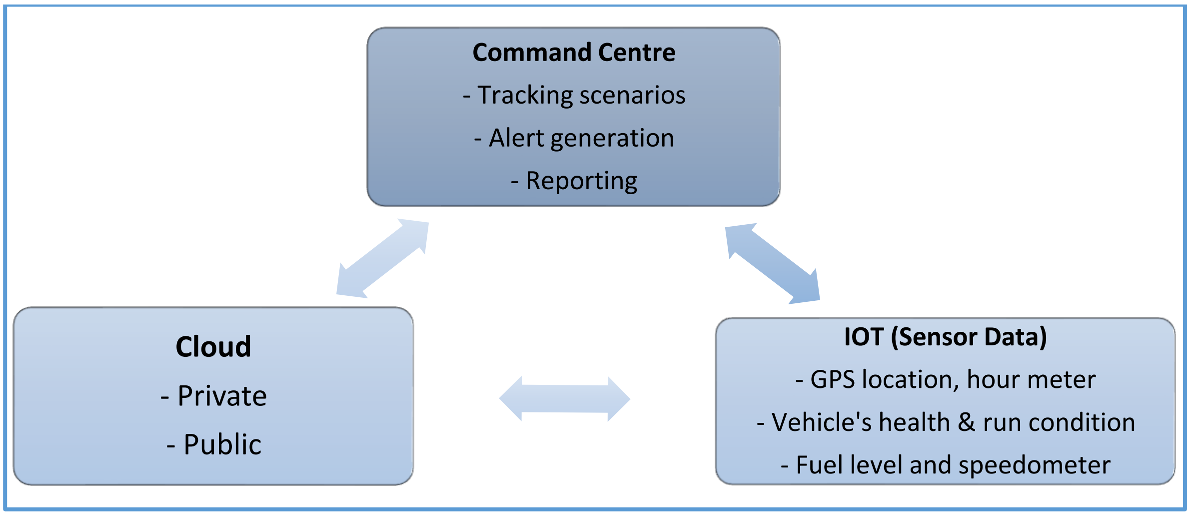

Figure 2.7: Effective approach to cognitive fuel management (Tata, 2018)

Tata (2018) describe the mode of operation of a cognitive fuel management system in six stages of data collection, data analysis, report generation, monitoring, emergency detection and data back up in a cloud facility. In the first stage, data in the system is collected by the different types of sensors on the equipment and the sensors strategically placed in the operating environment. For stages two and three, the command centre mainly tracks the data that is flowing in the system to generate reports on a routine basis. In stage five, when anomalies or emergencies are detected, the command centre also serves as an emergency response solution to alert responsible persons of the anomaly or emergency detected. Lastly, in stage six, the cloud facility is mainly for backing up of operational data and ensuring security of the operational data. The use of IOT technology for fuel management at Bathopele mine was a way of improving the process control and fuel use optimization.

2.7 Introduction of Short Interval Control to Fuel Management

Using IOT technology for fuel management at Bathopele mine enables the adoption of short interval control (SIC), which refers to a management process that enables workers to provide progress updates according to their task goals, and alert managers of issues or deviations in real time (Polymathian, 2021). Song et al. (2013) state that short interval control substitutes paper-reporting processes and thereby increasing integrity and integration of data. SIC empowers mines to monitor and review operational plans performance based on targets in real time, for immediate corrective action (ABB, 2021). Song et al. (2013) suggests that short interval control will in the future used to analyse trends and improve process, which will promote continuous improvement in underground mining. Goodman, Rajagopaul & Cassim (2019) suggest that for mining companies to achieve radical performance results, they must integrate mining, energy and information technology into mine process and design through innovation. Such integration has the potential to improve safety standards, save money, optimise the energy mix, and improve operational performance (Goodman, Rajagopaul & Cassim (2019).

The introduction of IOT to the fuel management system at Bathopele mine gave rise to several opportunities for improving production efficiencies. Before IOT was introduced, fuel management system at Bathopele mine was based on the use of operator checklists and manual record-keeping, which make it difficult to track the consumption and use of fuel. The old system relied completely on the accuracy of the information from the operator checklist. As a result of different equipment refuelling from the same storage area or refuelling vehicle, it was difficult to accurately collate the operator’s checklists to produce daily and monthly reports on the consumption of fuel.

2.8 Diesel Refund scheme

In order to boost the international competitiveness of primary production sectors, the diesel refund scheme (DRS) was introduced by the South African Revenue Services (SARS) from year 2000 in a phased approach (SARS 2017). The scheme offers eligible diesel users refunds on fuel and road accident fund levies on application (Pricewaterhousecoopers, 2019). On-land primary production sectors are eligible to apply for a rebate of forty percent (40%) of the general fuel levy and one hundred percent (100%) of the road accident fund (RAF) levy on eighty percent of qualifying fuel consumption (SARS 2021). According to StatsSA (2021) , the general fuel levy is a tax per litre of fuel and the RAF levy is used for the compensation of motor vehicle accident victims. The fuel price consists of four broad elements: namely basic fuel price, taxes and levies, retail and wholesale margins, and storage and distribution costs (StatsSA, 2021).

Good management and accounting of diesel records will enhance the chances of a successful application for the refund. To be eligible for the refund, taxpayers need to maintain accurate logbooks with information on diesel storage and volumes qualifying for a refund (SARS, 2017). The IOT technology used for fuel management at Bathopele mine provides an accurate database of information required for the application for the DRS. The mining and quarrying sector accounted for thirty-three and a half percent (33,5%) of the total diesel refunds administered by SARS from the 2010/11 to the 2015/6 financial years (SARS, 2017). Figure 2.8 indicates the appropriation of the diesel refunds per sector and indicates that the mining and quarrying sector received the second most refunds.

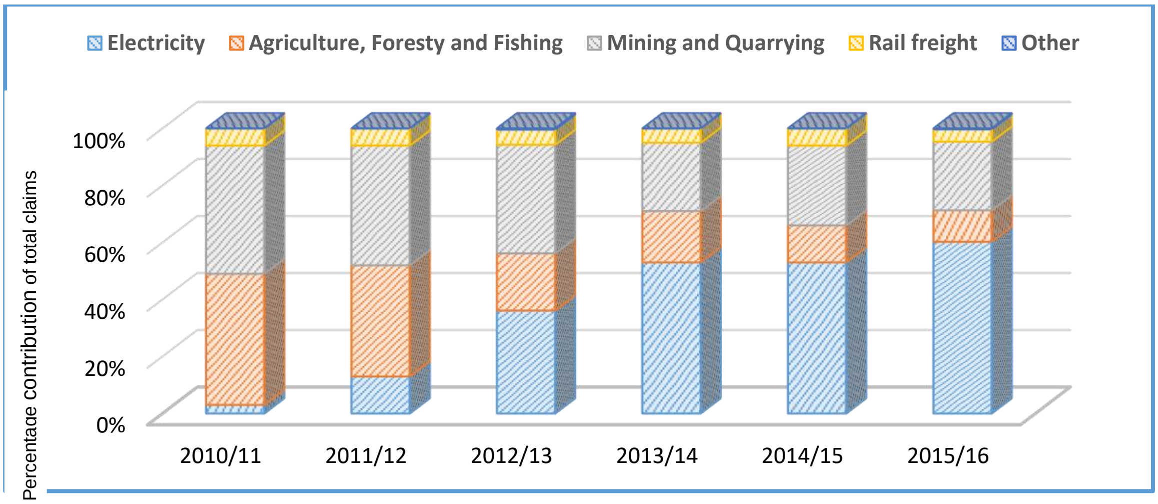

Figure 2.8: Appropriation of diesel refunds per sector from 2010/11 to 2015/6 financial years (SARS,2017)

The DRS is sometimes criticized for encouraging the use of fossil fuels such as diesel. SARS (2017) states that the diesel refunds in South Africa lowers the fuel input costs of primary users and potentially inefficiencies which may result in negative environmental impacts. The availability of information from the fuel management system has enabled the mine to apply for the Diesel Refund Scheme (DRS) with relative ease due to the records maintained by the system. Figure 2.9 shows the increases in fuel taxes in South African over a period of fifteen years, whereby the fuel levy increase by almost two hundred percent (200%), and the RAF levy by around seven hundred percent (700%).

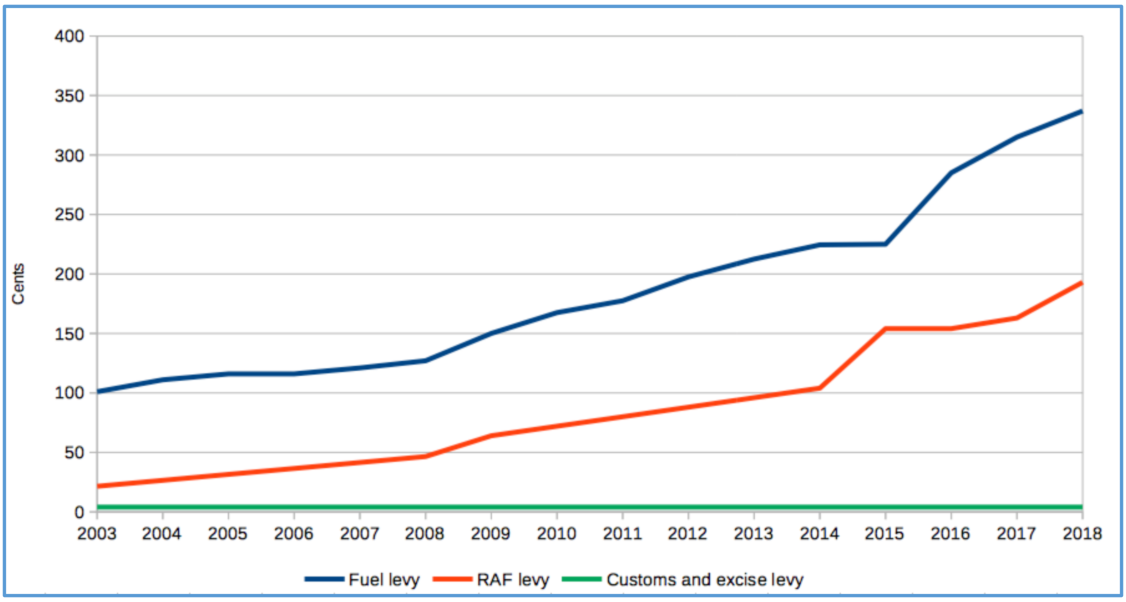

Figure 2.9: South African fuel taxes history (2003 to 2018) (Businesstech, 2018)

2.9 Sources of Power for The Mining Industry of The Future

The increasing depth of mining has led to the promotion of mechanised mining systems due to the ability to produce high volume quantities required for mines to be profitable (Fox, Greth & Kocsis, 2018). In the advent of global warming and environmental concerns related to mining activities, there is a consensus of the need to focus on green energy sources for the future. For existing mining operations, there is a push to move from LHDs or trucks powered by diesel engines to those powered by electricity, and more recently mining companies are exploring the use of hydrogen fuel cell energy.

2.9.1 Power sources for TMM engines in mining

Heavy industries around the world use different types of equipment with engines powered by different sources of power such as diesel, battery electric and electric engines. Skawina (2019) suggests that diesel engines are favoured due to their flexibility, durability, and high efficiency. The increasing fossil fuel prices may speed up the long-term objective of mining operations to decarbonize operations (Keen *et al.*, 2022).

(Fox, Greth & Kocsis, 2018) proposes a battery fleet for underground mines that will eliminate DPM and reduce heat load, which will lead to a safer mine environment and reduced costs. Fox, Greth & Kocsis (2018) states that mining companies will ultimately adopt battery powered engine use for equipment fleets due to their benefits over diesel powered equipment fleets and battery technology becoming more competitive. (Skawina, 2019) suggests that mines may find more benefits by changing the power source instead of replacing the diesel empowered equipment fleet. In the study LHD operations underground by (Skawina, 2019) found that diesel powered LHDs achieved higher production rates, faster travelling speeds and shorter cycle times than their battery powered LHDs. It also found that the energy cost per ton decreases with increasing machine size for diesel powered LHDs, where else energy cost per ton increased for battery LHDs. Mining companies intend to decrease diesel use across operations and electrify their truck fleets or use lower carbon fleets in order to minimize exposure to fossil fuels price volatility (Keen *et al.*, 2022). The challenges associated with the operation of diesel engines in mining has led to calls for transition new sources of energy for TMM in mining. Jacobs, Preis & du Plessis (2019) propose the development of a feasibility analysis framework to facilitate decision-making on the adoption of electric or diesel electric equipment. Bathopele mine has recently concluded trials on DPM filters that have the potential of eliminating up eighty percent of the emissions on LHDs.

2.9.2 Emissions from diesel engines

The exposure to diesel engine exhaust fumes to mine workers is of major concern all mines, but particularly for the underground mines which rely on ventilation systems to dilute and remove particles and gases from working places. The emission from the exhaust of diesel engines contains both particles and gases (Jacobs, Preis & du Plessis, 2019). In the Mine Health and Safety Council's report regarding the implementation of the Diesel Particulate Matter emission reduction program, the main aims were to transition and to reduce mine worker exposure to DPM (Jacobs, Preis & du Plessis, 2019). According to Maximilien et al. (2017), the exposure to diesel engine exhaust fumes has been associated with cancer and cardiopulmonary diseases. In their study of the diesel exhaust exposures of two underground mines, Maximilien et al. (2017) found that although various engineering and administrative measures were in place, the exposures remain a concern and the health of the workers must be prioritized.

At Bathopele mine, a number of fuel filters are currently being trialed with the objective of reducing diesel particulate matter (DPM) emissions to within international standards. Jacobs, Preis & du Plessis (2019) recommend a progressive three-step approach to the reduction of exhaust emissions. The first step is to implement a diesel fuel supply chain management; secondly to ensure sufficient quality diesel is used in the equipment; and thirdly to determine the prevailing emissions gap, institute requisite repairs to achieve OEM specifications (Jacobs, Preis & du Plessis, 2019).

2.9.3 Fuel cells technology

Government policy and public demand has led the heavy industries such as mining towards the use of zero emission heavy equipment (Pocard, 2021). Fuel cell electric power systems are an emerging technology that offer benefits such as reduced emissions and noise, and as well as improved efficiency of the equipment (Office of Industrial Technologies, 2001). Pocard (2021) states that hydrogen fuel cells provide the advantage of being the zero-emission option that matches diesel’s service range, payload capability and performance. One of the major mining companies, Anglo American (2022) has committed to achieving carbon neutrality by year 2040 and have recently unveiled a prototype of the world’s largest hydrogen-powered mine haul truck at its Mogalakwena platinum mine. The plan is to replace the entire fleet of diesel-powered trucks with trucks fueled by green hydrogen, which could reduce diesel emissions at the open pit by eighty percent (80%) (Anglo American, 2022). Hydrogen fuel cells generate power through the convertion of chemical energy into electrical energy by converting hydrogen gas and oxygen into water (Anglo American, 2019). Figure 2.10 shows the basic operation of fuel cell technology.

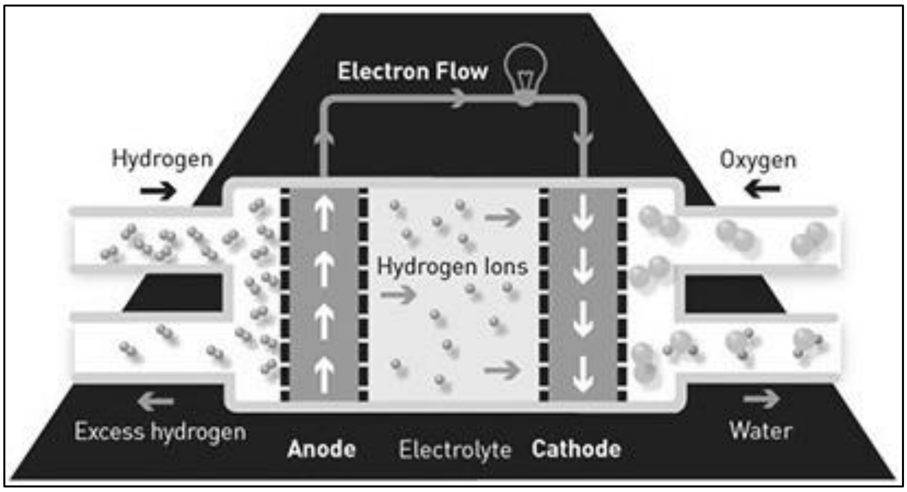

Figure 2.10: Operation of Fuel Cell technology (Anglo American, 2019)

According to (Pocard, 2021), fuel cell powered equipment offer benefits such as better availability due to reduced refueling time, higher power output because of greater energy density, and more refueling infrastructure options over battery powered equipment. Like battery electric powered TMM, the development of hydrogen fuel cell powered TMM will require substantial investment and research for adoption by the mining industry which is currently ongoing.

2.10 Theory of Constraints

The Theory of Constraints (TOC) was developed by Eliyahu M. Goldratt in 1984 and has been used extensively in various industries for business improvement initiatives. The TOC has for more than three decades been implemented successfully in most sectors by many companies of different sizes (Şimşit, Günay & Vayvay, 2014). The TOC problem solving methodology was developed to improve the performance of industrial systems and has been applied extensively in the mining sector as well. According to Odendaal (2011), the TOC method may be applied to reduce operating costs without significant increases to capital or operational expenditure.

TOC is a problem-solving approach that focuses on the weakest link in the chain (process) to improve the performance of the system (Şimşit, Günay & Vayvay, 2014). The weakest link is also referred to as the system constraint. According to Goldratt (1990), a system constraint is anything that prevents the system from achieving a better output compared to its objectives. The original TOC approach comprises of the following steps:

i. Identifying the system’s constraint(s)
ii. Decide how to manage system constraint(s)
iii. Subordinate everything else to the above decision.
iv. Elevate the constraint.
v. If in any of the above steps, a constraint has been broken, return to step one.

Through application of the TOC, management may influence the production cycle and increase production capacity (Pozo et al., 2009). According to Ramasu, Sobiyi & Akinlabi (2017) the TOC may be applied to processes involved in primary mining activities. In the research study, the TOC will be applied to the refuelling cycle at Bathopele mine to identify system constraints and find areas of improvement.

In conclusion, this chapter explored the various application of IOT technologies in different industries including the mining sector. Fit-for-purpose infrastructure and security features are important for the operation of the IOT technology system. IOT applications in mining are broad, and there are benefits for improving process control. Alternative power sources for TMM in mining must be explored through research and application in line with the global imperative to move towards green energy. The Theory of Constrains is a problem-solving tool which was used to determine bottlenecks in the fuel management system at Bathopele mine.

3. RESEARCH METHODOLOGY

This chapter presents the research methodology that was adopted and followed for the research. It will include the nature of the research conducted, the methods and tools used, sources of the data, data analysis techniques, the assumptions, and limitations of the research. Figure 3.1 below indicates the steps followed in the report to achieve the objectives of the research.

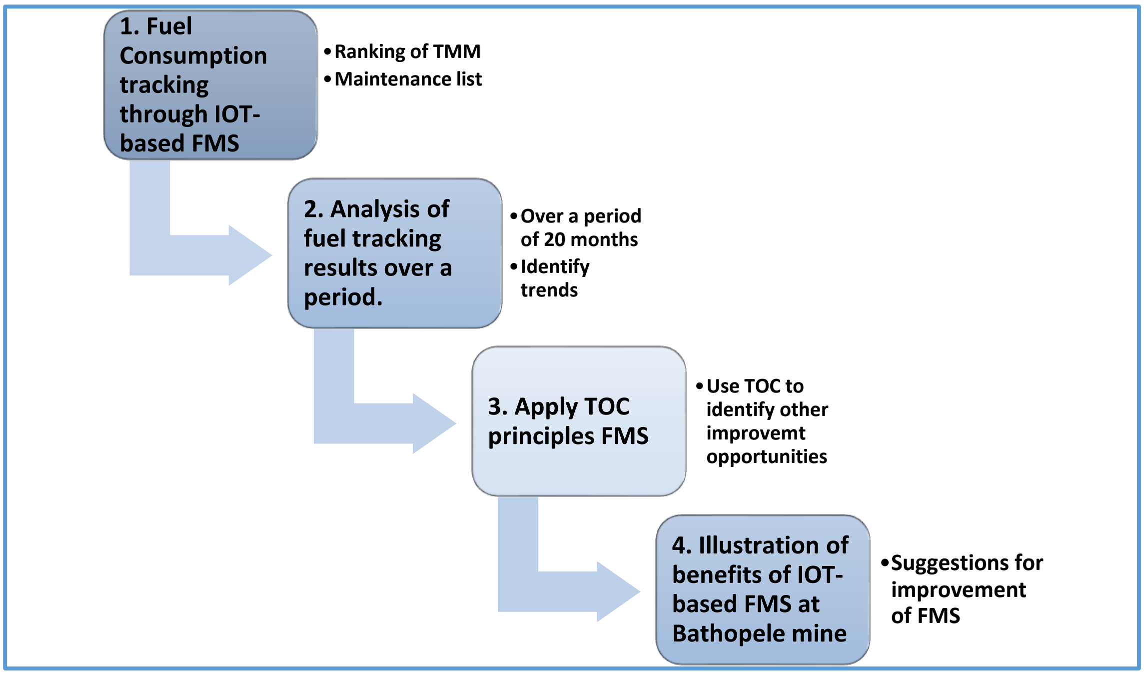

Figure 3.1: Research methodology for the dissertation

3.1 Nature of the Research

Deb, Dey & Balas (2019) outline three main types of engineering research as descriptive or analytical research, applied or fundamental research, and quantitative versus qualitative research. This research study has descriptive, applied, qualitative and quantitative characteristics.

3.1.1 Descriptive versus Analytical

Descriptive research approach was followed for the study. According to (Deb, Dey & Balas, 2019), descriptive research comprises of comparative and correlational methods as well as fact-finding examinations to describe the present state of subject. The purpose of descriptive research as to describe, explain and validate research findings (Dudovskiy, 2021). The main objective of this type of research to describe the circumstances of the problem being studied. In this case, the benefits of using the internet of things for fuel management will be discussed in this research study.

Another important characteristic of descriptive research is that the researcher has no control over the variables being studied (Dudovskiy, 2021). Descriptive research follows deductive theory, which represents the common view of the foundation of the relationship between theory and research (Bryman et al., 2014). Figure 3.2 shows steps followed by the deductive research approach. The first step is theory, followed by the formulation of the hypothesis, collection of data, findings, confirmation or rejection of the hypothesis and revision of the theory. This approach is followed for the correlation analysis in the research study.

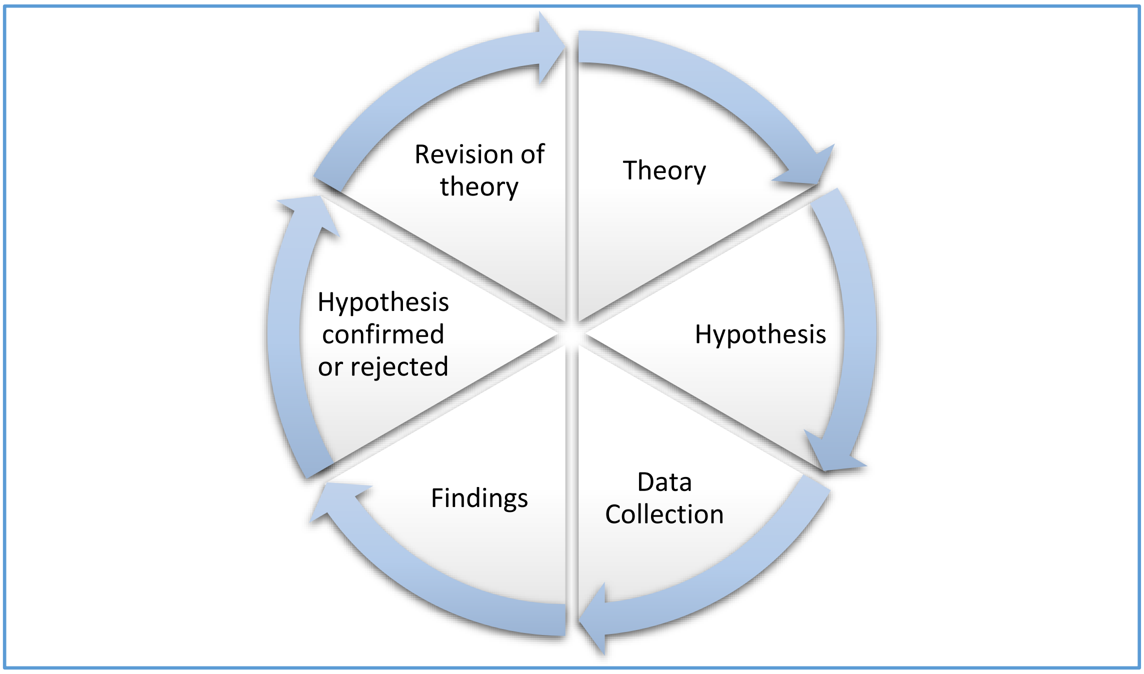

Figure 3.2: Deductive research approach (Bryman et al., 2014)

The other type of research is analytical research, which makes use of available data for analysis and critical evaluation (Deb, Dey & Balas, 2019). This type of approach is also called inductive research. According to Bryman et al. (2014), in the inductive approach, theory is the outcome of the research. The research study was carried out based on the deductive approach.

3.1.2 Applied versus Fundamental

Deb, Dey & Balas (2019) suggest that while fundamental research is focused on generalizations and formulations of theory, applied research intends to resolve immediate problems facing the organization. Applied research involves the use of established theory to understand and resolve day to day problems. The main objective of applied research is to develop solutions for existing problems in organizations (Deb, Dey & Balas, 2019). The research study is a form of applied research where existing theory is being applied to a problem to derive solutions.

3.1.3 Quantitative versus Qualitative

The research study uses both quantitative and qualitative research methods. Quantitative research comprises of the collection of numerical data and statistical observations to draw conclusions (Deb, Dey & Balas, 2019). According to Bryman et al. (2014) the qualitative research method relies on words instead of numbers in the collection and analysis of data. Both research methods can be used simultaneously in what is also referred to as the combined research. Although, there may be practical difficulties with application, combined research is popular in business and management research (Bryman et al., 2014). Similarities between quantitative and qualitative research include data reduction, answer research questions, draw analysis and finding from literature, uncovering and presenting variation, frequency as basis for analysis, attempt to prevent deliberate distortion, importance of transparency and address the question of error (Bryman et al., 2014).

3.2 Research Methods

Various quantitative and qualitative research techniques were applied in the research study. The four fundamental research methods used in the research study are shown in figure 3.4.

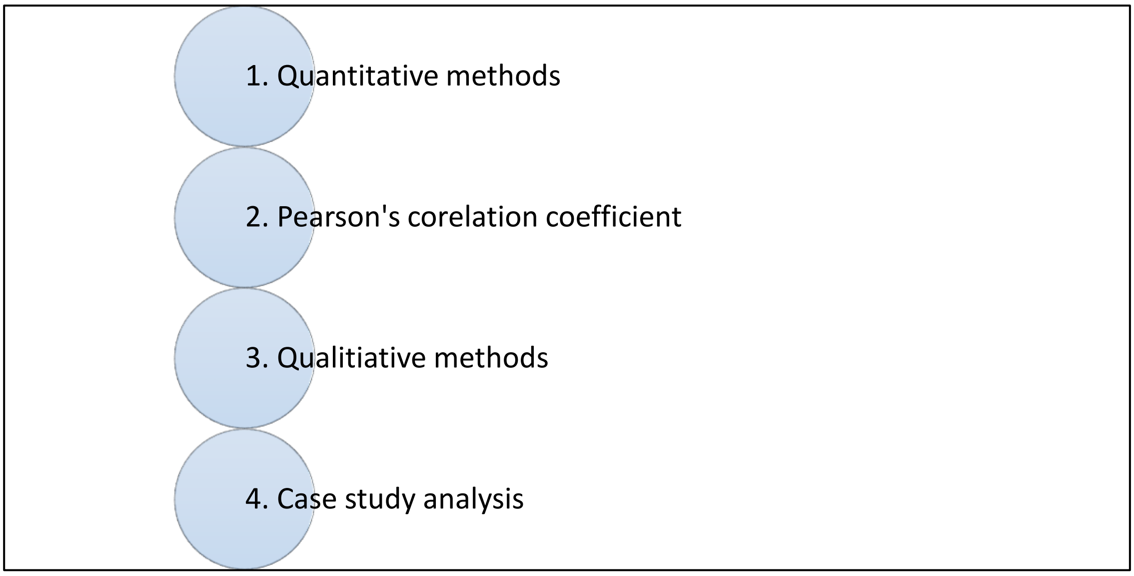

Figure 10: Fundamental research methods used

3.2.1 Quantitative methods

i. **Time studies** conducted to determine the time taken by a Lubricant and Fuel Utility Vehicle (Lube UV) to travel from surface to refill TMM underground, and therefore sum up all the activities of the refueling cycle.

ii. **Statistical analysis** through selected measures of dispersion relevant for the research which include arithmetic mean, median, range, variance, and standard deviation.

iii. **Bivariate analysis** determines if a relationship occurs between two variables (Bryman et al., 2014). For the research study, the analysis will be done using the Pearson’s correlation coefficient (r). Schober & Schwarte (2018) state that bivariate normal distributions have two properties; variables are normally distributed, and that the relationship between the variables is linear.

3.2.2 Pearson’s correlation coefficient (r)

According to Schober & Schwarte (2018) Pearson’s correlation coefficient r, is a measure of the association between two variables, whereby as the value of one variable changes, so does the value of the other variable. Bryman et al. (2014) state that Pearson’s correlation coefficient analyzes the strength of the linear relationship between two interval or ratio variables. To calculate Pearson’s correlation coefficient r, the following formula is used:

$$r = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2][n\sum y^2-(\sum y)^2]}}$$ ……………………………….[1] (Glen, 2022)

The key characteristics of Pearson’s correlation coefficient (r) with respect to the association of two variables are as follows; if r = 0 (no relationship) and if r = 1 (perfect/linear relationship), the closer r is to 1 the stronger the relationship, the closer r is to 0 the weaker the relationship, a positive or negative coefficient indicates the direction of the relationship, a value of +1 shows a perfect positive relationship, and a value of -1 shows a perfect negative relationship (Bryman et al., 2014). The scatter plots in Figure 3.5 shows the different associations of the variables; Plot in (a) shows no relationship, Plot (b) shows an example of a weak negative relationship, Plot (c) indicates a moderate positive relationship, Plot (d) indicates a moderate positive relationship, Plot (e) shows a strong positive relationship, and Plot (f) indicates and examples of a very strong negative relationship (Bryman et al., 2014).

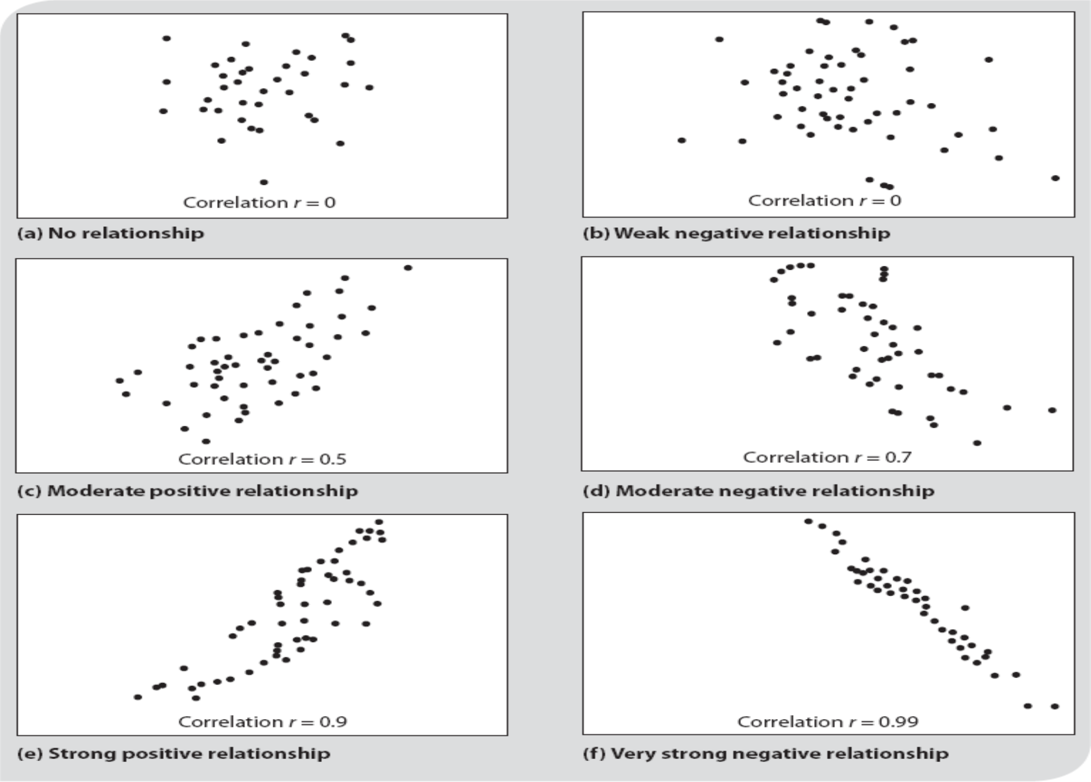

Figure 3.5: Pearson's correlation coefficient examples (Bryman et al., 2014)

Schober & Schwarte (2018) propose two assumptions that must be applied for proper inference on the strength of the association of the relationship between the data from a population. Data must be obtained from a random or a representative sample, and both variables are continuous, jointly normally distributed, and random variables. It is also important to determine whether the outcome of Pearson's correlation coefficient is statistically significant. This test will determine how confident we are that our findings based on a sample will also be found in the population (Bryman et al., 2014). A significant correlation coefficient also confirms that the linear graph, which is also referred to as the regression line, may be used for prediction (Lumen, 2022). The level of significance is normally expressed in statistical terms, and in business the maximum level of statistical significance that is acceptable is $\rho < 0.05$, which suggests that there is less than five percent (5%) chance that the sample shows a relationship that does not exist in the population (Bryman et al., 2014). Similarly suggesting a ninety five percent (95%) probability that the relationship does exists. The ninety five percent (95%) critical values of sample correlation coefficient table are contained in appendix B. To confirm the significance of the relationship, we need to compare the r value to the associated critical value in the table, and if r is not between the negative and positive critical values then the correlation coefficient is significant (Lumen, 2022).

3.2.3 Qualitative methods

Non-participant observation method is used for the research study and suggests that during the research study the observer did not participate in the activities observed. It was a form of an unstructured observation. According to Bryman et al. (2014) the objective of an unstructured observation is to record the details of the actual activities in order to derive findings.

3.2.4 Case study

Case study analysis makes use of a wide variety of sources of quantitative and qualitative evidence. According to Bryman et al. (2014) the database of the case study analysis will include the following: visual documents, archival records, interviews, field noted, recordings of direct observation, participant observation and artifacts.

3.3 Research Questions

The research study aims to answer the following questions:

I. What benefits were derived by the introduction of IOT to the fuel management system at Bathopele mine?
II. How can the fuel management system at Bathopele mine be used to improve production output?
III. What is the relationship between fuel consumption and production output at Bathopele mine?

3.4 Data Sources and Analysis

The primary data used in the research study was obtained from Bathopele mine through observations made during specific periods and analysis of refuelling data from April 2019 to July 2021. As shown in Table 3.1, the primary sources of data were derived from Bathopele mine, and the secondary sources of data from the literature study. Table 3.2 describes the aims of the various sources of data used in the research study.

Table 3.1: Source of data used for the research.

Sources of data	Primary sources	Cycle time studies
		Refuelling system reports
		Mine reports
		Personal observations
	Secondary sources	Peer-reviewed journal articles
		Other research: Published books, internet search, and industry appriaisal reports

Table 3.2: Sources of data and the aims

Source of data	Aim
Cycle time studies	To establish the current constraints in the refuelling system
Refuelling system reports	To analyse the fuel management system
Personal observations	To study mine reports and observe the fuel management system
Peer-reviewed journal articles	To derive background theory and study research relevant to the study
Other research: Published books, internet search, and industry appraisal reports	To derive background theory and study research relevant to the study

3.5 Assumptions and Limitations

Several assumptions were made in carrying out the research study due to the large fleet of TMM in use at Bathopele mine and the large size of the operation. The research is based on primary data from Bathopele mine.

3.5.1 Assumptions

Several assumptions were made in the collection, treatment and analysis of data used for the research study. Firstly, although the distance travelled by the refuelling equipment varied between different workplaces, the average distance to workplace was used for the time studies. Different types of LHDs from different OEMs are used at Bathopele mine, but as a second assumption an average consumption rate per LHD was used. Lastly, to use Pearson's correlations coefficient, an assumption was made that the relationship between fuel consumption and production output at Bathopele mine is linear due to the high number of TMM in use at the mine.

3.5.2 Limitations of the research

The research was conducted at Bathopele mine only, and hence the conclusions of the study are biased towards operations at Bathopele mine. However, the key findings will have applications at other similar underground trackless mining operations. Secondly, only the fuel consumption was tracked as the infrastructure to monitor the consumption of lubricants was not yet installed at the time of the study. Thirdly, the consumption of fuel is only tracked from the main storage tanks on surface and underground, and there are no means of tracking the fuel from the Lube UV into the different primary production equipment. Therefore, the data on the consumption of fuel by equipment only refers to the consumption from the bulk storage areas, but some of the machines are refilled in the working places and are only accounted for by tracking the lube UV that supplied fuel to that workplace for that shift.

The research methodology described in this chapter is applied to the Bathopele mine case study to achieve the aims of this research. Although the primary sources of data were obtained in specific areas of the mine, they reflect the operations due to the similarity and consistency of the mining cycle activates at Bathopele mine.

Lastly, in this chapter the details of the nature and type of research were discussed, and research methods were described. The main research questions were developed, and the associated data sources were identified. The assumptions and limitations of the research were also discussed.

4. BATHOPELE MINE BACKGROUND, REFUELLING INFRASTRUCTURE, EQUIPMENT AND REFUELLING CYCLE

The chapter describes the location of Bathopele mine with respect to the Bushveld complex, and the surrounding mines. The physical and geotechnical characteristics of the orebody are discussed, and a general overview of the mining method is provided. The main infrastructure and equipment in use at Bathopele mine is detailed. A detailed overview and analysis of the fuel management system at Bathopele mine is discussed. To determine the nature of the relationship between the consumption of fuel and output from Bathopele mine, a correlation study is conducted.

4.1 Location, Orebody, Mining Method, and Layout

Bathopele mine is part of the Rustenburg Platinum Mine (RPM) operations of Sibanye Stillwater and located on the western limb of the Bushveld complex as shown in Figure 4.1. The RPM section also comprises of three other operating mines; Khuseleka, Siphumelele and Thembelani which are all mining deeper sections (300 to 1200 metres below surface) of the mineral resource through conventional mining methods.

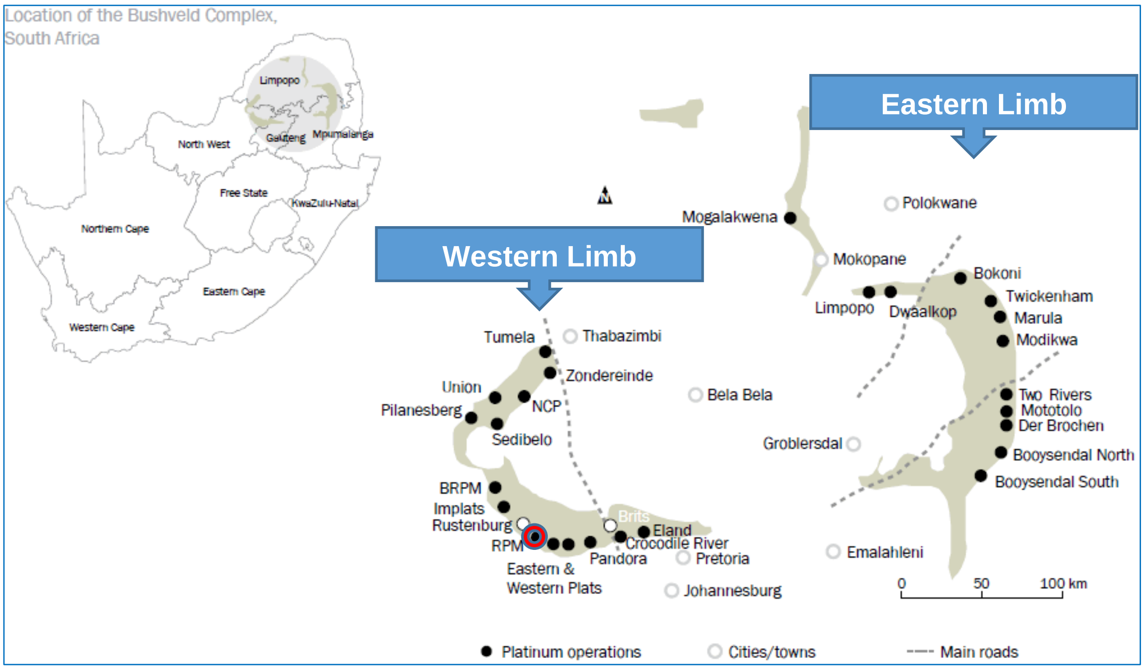

Figure 4.1: Layout of the Bushveld Complex (Minerals Council of South Africa, 2020)

4.1.1 Mine location

The shallow portion (less than 300 metres below surface) of the Bushveld complex is generally accessed through bord and pillar mining methods and making use of TMM. Bathopele mine, Kwezi, K6, Simunye, Kopaneng and Bambanani shafts are the bord and pillar trackless mining operations of the Sibanye Stillwater platinum segment. The relative lease areas and mining boundaries of the trackless operations in shown in Figure 4.2.

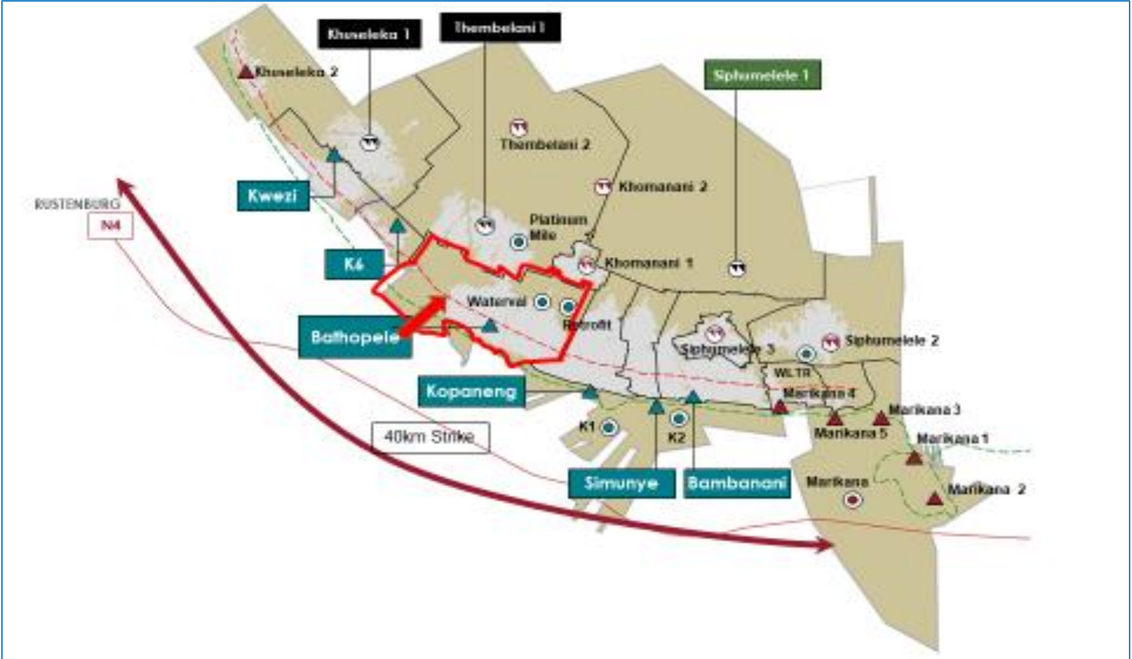

Figure 4.2: Sibanye Stillwater's Rustenburg and Kroondal operations

4.1.2 Mining method and layout

As discussed in preceding sections, Bathopele mine makes use of the Bord and Pillar mining method to extract ore from underground from a decline shaft system. The main design parameters of the bord and pillar mining method include pillar dimensions, panel span, stoping width, depth of mining and panel width. According to Anani (2016), the bord and pillar mining method is more suited for near horizontal deposits (less than 30°) in metalliferous orebodies at moderate depth.

The Factor of Safety (FOS) is used a decision criterion on the pillar dimensions and sizes, with a FOS of 1.5 as the minimum requirement. The main objective of the bord and pillar mining method is provided for optimal extraction of ore in the safest way possible (Anani, 2016). The same can also be said about most other mining methods. Table 4.1 shows the design parameters for Bathopele mine.

Table 4.1: Pillar design parameters

Bathopele mine bord and pillar mining method design parameters	
Parameter	**Range**
Pillar dimensions	5 to 8 metres long x 4 to 7 metres wide (Varies depending on
Panel span/length	4 to 10 metres
Stoping with	180 to 210 centimetres
Depth of mining	50 to 200 metres

A typical bord and pillar mining section at Bathopele mine comprises of ten bords mining in strike direction. Various production activities are conducted simultaneously in a mining section. Figure 4.3 shows the typical layout of a low-profile mining strike section at Bathopele mine.

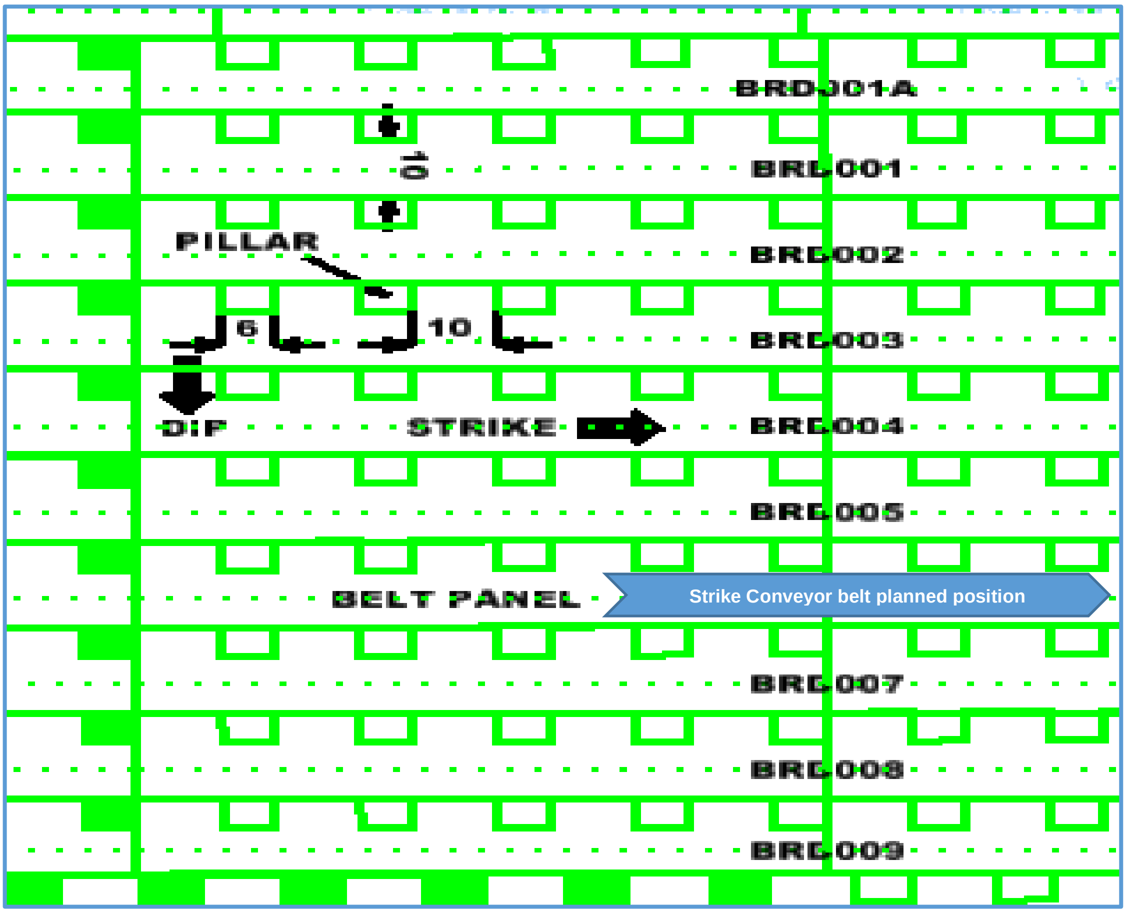

Figure 4.3: Typical Layout of an LP section mining at Bathopele mine

The mining cycle comprises of eight main activities which are undertaken on each shift by the mining team assigned to the section. The first activity is observing the re-entry period after the blast from the previous shift, and this period at Bathopele mine is a minimum of ninety (90) minutes. The second activity involves the cleaning of blasted ore by means of an LHD. The third activity is to support the blasted end and is conducted through the use of a roof bolter machine. Step five of face preparation is done by a combination of activities including watering down, hand-lashing and marking of the drilling holes. Activity number six of drilling is performed using a drill rig. In step number seven, a charging up UV is used to pump emulsion explosives after the fuses have been inserted into the drilled holes. The final activity of blasting is done using the blasting control unit (BCU) on surface after all the connections are completed underground. Blasting is only conducted once at a scheduled time for all underground workplaces by the BCU system. In Figure 4.4, the main activities of the mining cycle at Bathopele mine is illustrated.

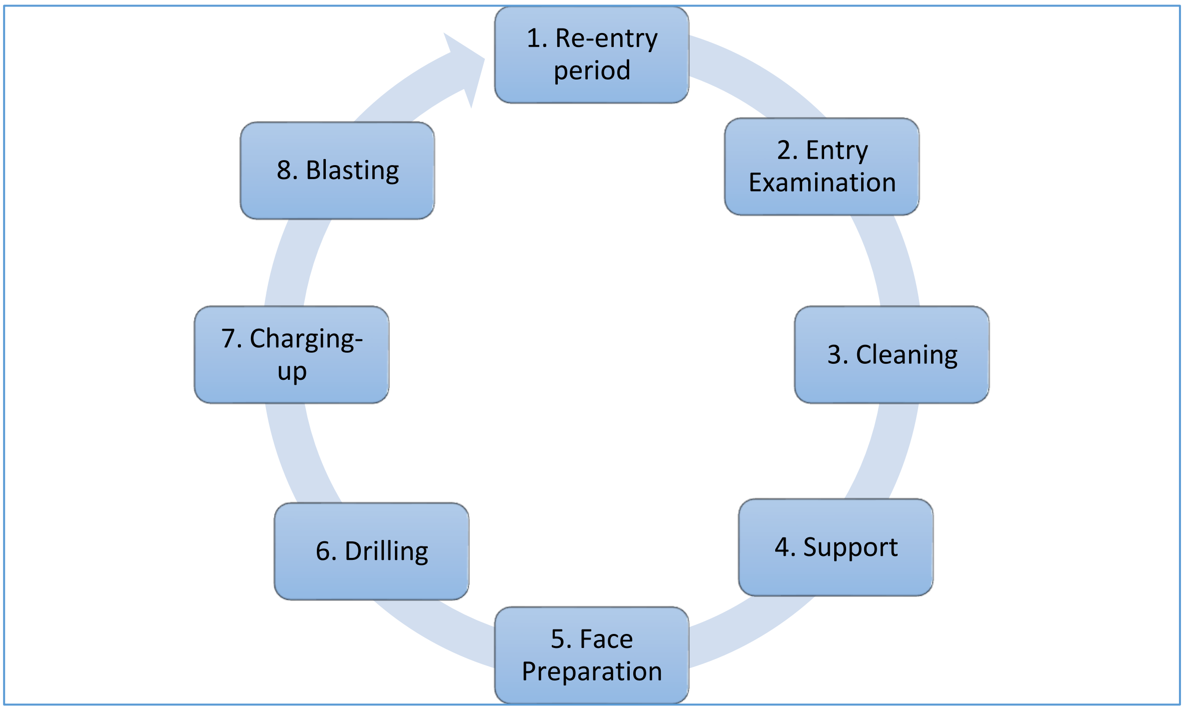

Figure 4.4: Mining cycle steps at Bathopele mine

4.2 Mine Infrastructure and Equipment

Infrastructure and equipment ensure that the output from the mining activities is brought to surface in an effective and efficient manner. Bathopele mine comprises of two decline shafts (East and Central shafts) both fitted with conveyor belts feeding the mine silo with ore from the underground sections. The decline shafts provide access to underground sections and are used for transportation of men, material, and all other logistics operations in support of the production activities. TMM from various OEMs are in use at Bathopele mine, and hence each shaft is equipped with an underground workshop in addition to the main TMM workshop on surface for to conduct both scheduled and unplanned maintenance activities.

4.2.1 Mine Infrastructure

The main infrastructure components of Bathopele mine include conveyor belt installations, electrical installations, pumps and associated pipelines, fans, refuelling infrastructure, access roadways, in-stope installation and in-section infrastructure. However, for the purpose of this study, the focus is on refuelling infrastructure and TMM operations.

4.2.2 Type of equipment in operation

Both East and Central shafts make use of similar TMM units, albeit from different manufacturers. Personnel carriers and Jeeps are used for the transportation of men and materials to and from underground. UVs are used for the transportation of fuel and lubricants, emulsion and most of the material required for production activities. Primary production equipment includes LHDs, roof bolters and drill rigs.

4.3 Refuelling Infrastructure and Equipment

The refuelling infrastructure at Bathopele mine comprises of the bulk storage tanks on surface with capacities of between 60 000 to 80 000 litres. The tanks are used for the temporary storage of fuel, lubricants, and coolant, and they are connected to the underground workshops by means of pipelines to allow for the refilling of TMM.

4.3.1 Refuelling process

There are two main ways to refill production TMM at Bathopele mine. The first option is to drive the TMM to the refilling bays either on surface or underground, and the second option is to transport fuel and lubricants to the production sections and refill TMM there. Option one is normally used for refilling secondary production equipment, and where else option two is used for primary production equipment. However due to unplanned downtimes, either option may be used where required. In general, there are four ways in which primary production TMM at Bathopele mine may be refilled as shown in Figure 4.5. Option one is the most efficient channel as it keeps production equipment in their sections, followed by option two where primary TMM are refilled at the underground workshops and then travel to the sections. Options three and four are list efficient as they involve TMM travelling from surface. Although option four also involves primary TMM not leaving their workplaces, it also relies on the Lube UV travelling from surface to underground to deliver fuel and lubricants.

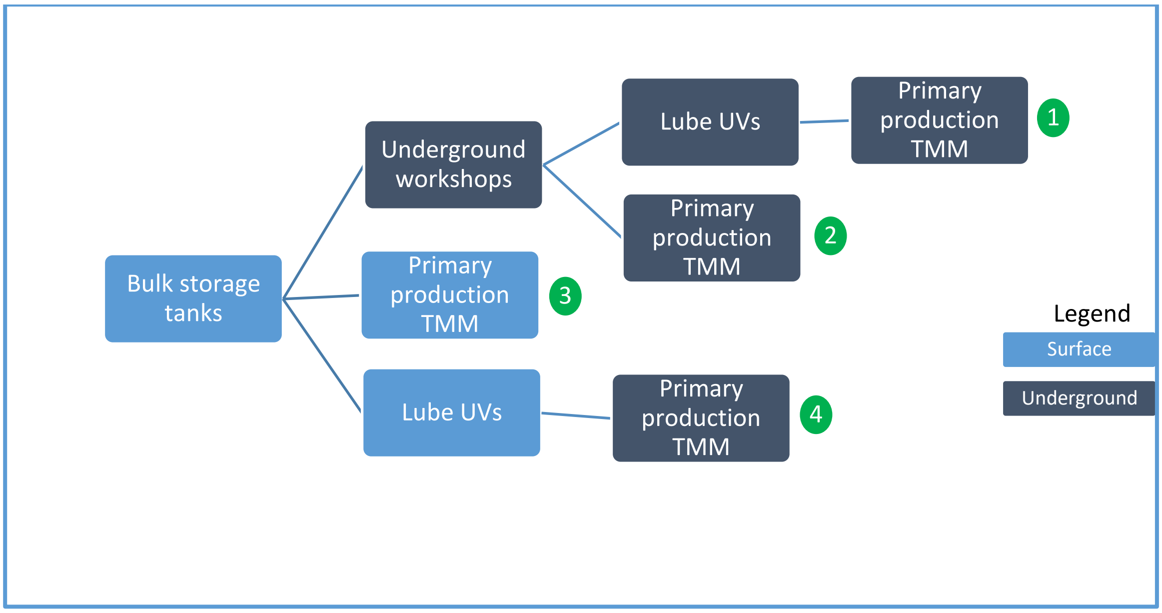

Figure 4.5: Channels for refilling TMM at Bathopele mine

The normal fuel flow at Bathopele mine follows steps as shown in Figure 25 in the next section. Fuel is delivered on site by the supplier which is then stored in the surface bulk storage infrastructure.

4.3.2 Bathopele mine's IOT-based fuel management system

On surface fuel level sensors are installed to monitor the levels of fuel and lubricant stocks. The information of the inventory levels is constantly displayed in the control room, the system will give a warning signal once stocks are below thirty 30 percent of storage capacity. Tag readers are installed at the refuelling bay and on all TMM and are used to regulate access to fuel and lubricants. Tag readers are coded and named according to the area or equipment that they are installed on. Each TMM operator is issued with a unique refuelling card that will be used for access to fuel or lubricants which is linked to the employee card through their industry number for identification. A similar process is followed when UVs that transport fuel and lubricants to underground sections arrive to refill TMM in the workplace. The operator of the TMM is expected to produce a refuelling card and scan it on the tag reader connected to the UV to access fuel or lubricants or both. The IOT components installed on the fuel flow process are also shown in Figure 4.6.

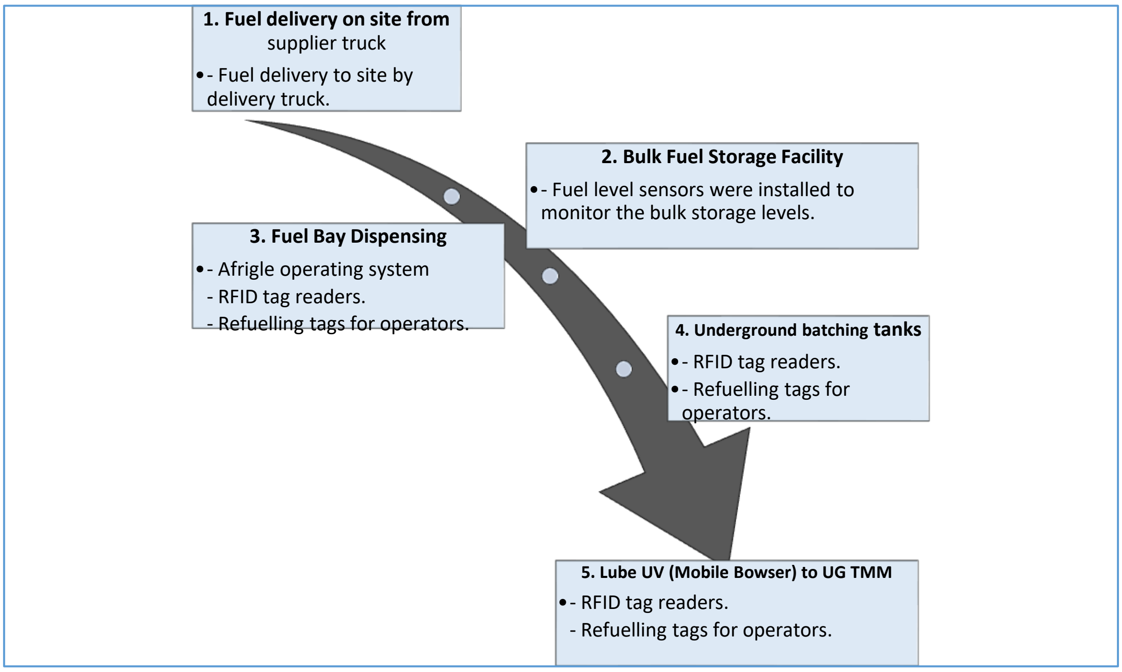

Figure 4.6: Fuel flow process at Bathopele mine

The information from all the refilling activities is generated as output reports at the end of each production shift for analysis by mine supervisors and management.

4.4 Refuelling Cycle

The normal refuelling/refilling cycle at Bathopele mine for primary production TMM involves the use of Lube UV to transport fuel and lubricants from the bulk storage containers to the TMM in the working places. At start of shift, the lube UV operators conduct a safety meeting and thereafter proceed to the equipment to complete the UV's pre-use checklist. The UVs are then trammed to the underground TMM workshops where they are going to hook a refilling cassette after it has been topped up. Thereafter the Lube UV that transports the fuel and lube to the underground sections. The following formular was used to calculate the total refuelling cycle time:

Operator safety meeting (OS) + UV checklists (UC) + Tramming time (TT) + Refuelling time (RT) = Total cycle time (TCT)…………………………………………………………….[4.1]

Time studies were used to track the movement of each UV from surface to the production sections, back to the underground workshop and then back to surface once refuelling activities are complete. The total cycle time according to the time studies that were done is approximately 690 minutes as shown in Figure 4.7. The average time taken per activity was studied over a period of two weeks.

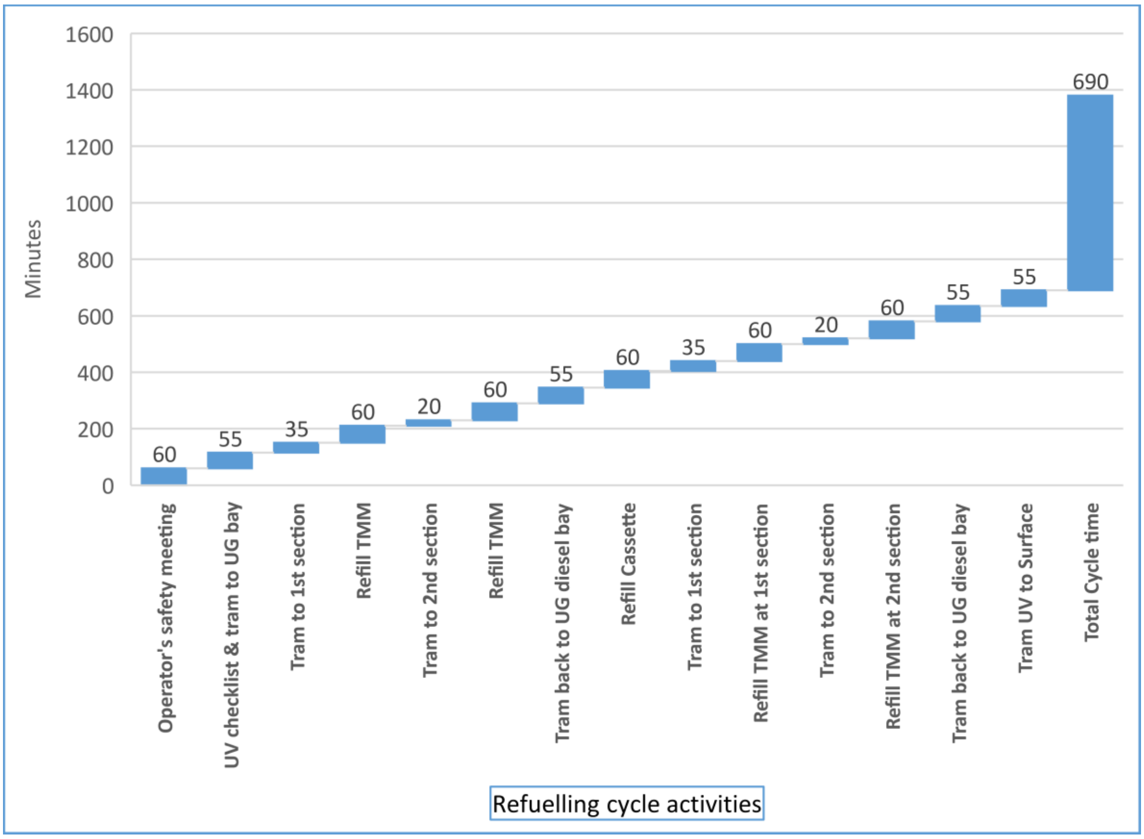

Figure 4.7: Steps in the refueling cycle at Bathopele mine

In Figure 4.8, the main refuelling activities were grouped into four main activities; operators' safety meeting and completing the UV checklist, tramming, refilling TMM and refilling the lube cassette. The results show that tramming of the lube UV to and from bulk storage areas to primary production TMM accounts for forty eight percent (48%) of the cycle time, followed by thirty five percent (35%) time taken refilling primary production TMM in the sections. The remaining seventeen percent (17%) of the time is used for the operators' safety meeting and filling up the lube cassette.

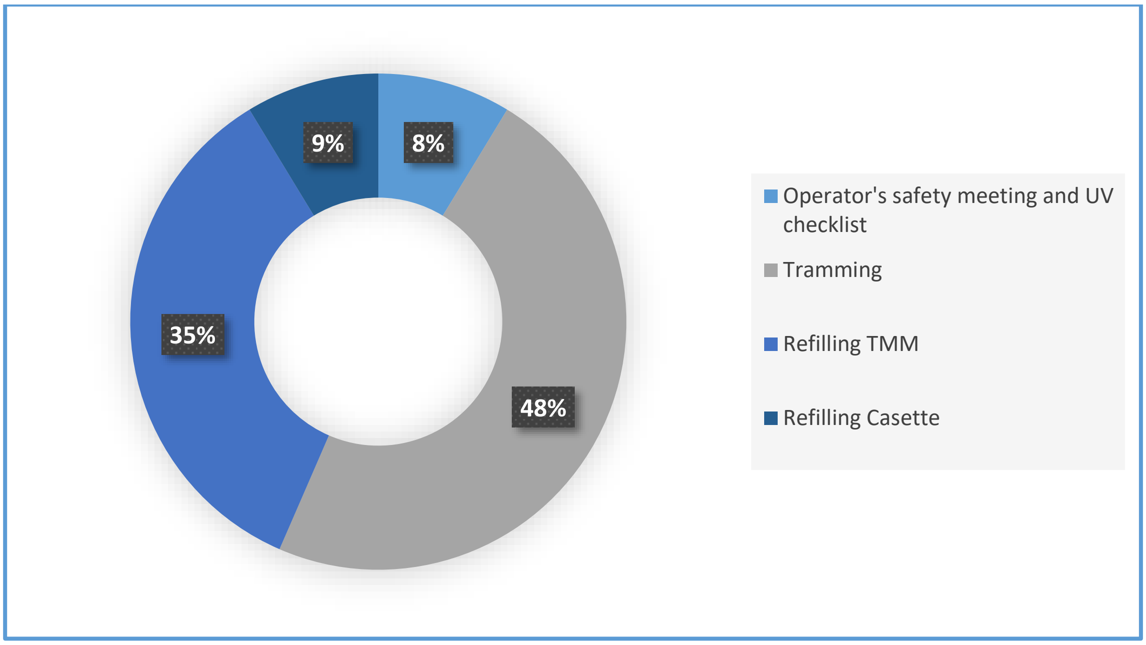

Figure 4.8: Contribution of the activities to the total refueling cycle at Bathopele mine

4.5 Application of the Theory of Constraints (TOC)

The five step TOC approach was implemented Bathopele mine with focus on the refuelling process in a phased approach; identifying the constraint, deciding how to manage the constraint, subordinating all to the above decision, elevate the constraint, and returning to the first step when the constraint is broken.

4.5.1 Identifying the constraint

Identifying the constraint is the first step in implementing the TOC. Time studies were conducted on the refuelling process, and analysis of shift reports on refuelling activities were done. The results as shown in Figure 4.9, indicate that the activity that takes the most time in the process is tramming of the lube UV.

Therefore tramming/travelling of the lube UV to and from bulk storage to primary TMM is the constraint of the refuelling process.

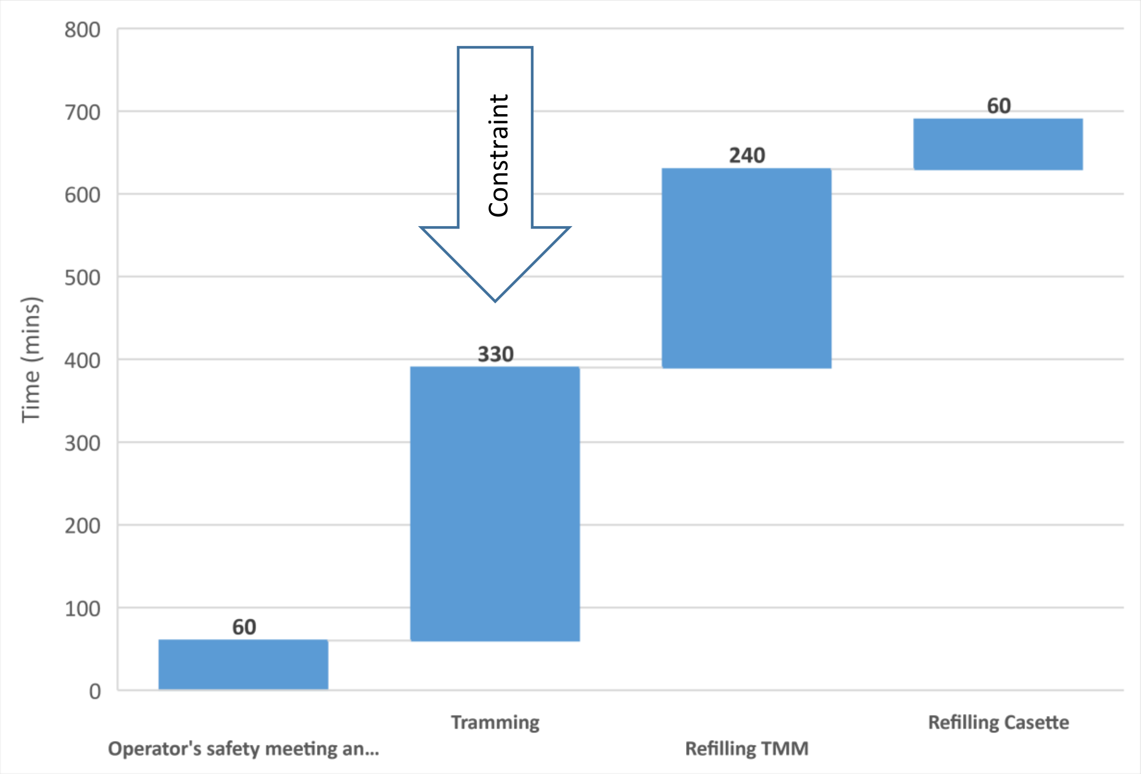

Figure 4.9: Refueling cycle time main activities

4.5.2 Management of the constraint

Deciding how to manage the tramming activity was the second step in the TOC implementation process. The tramming distance is the main contributor to the various tramming times, and an assumption was made that Lube UVs tram with the same speed on average which is the safe allowable speed. Therefore, since the distance to underground sections will continue to increase as mining progress, there was a need to explore other options. In Figure 4.10, the different tramming activities in the refuelling cycle are illustrated and tramming to and from surface account for thirty four percent (34%) and tramming between the underground bay and sections takes up sixty six percent (66%) of the time.

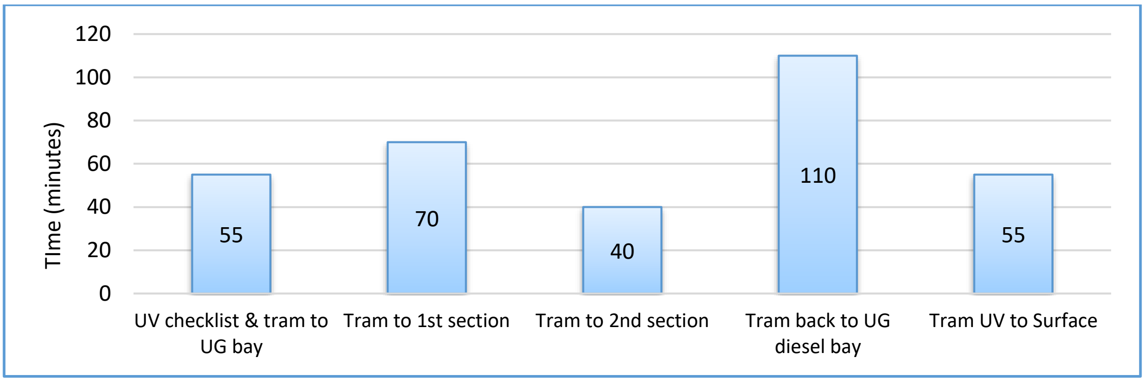

Figure 4.10: Breakdown of tramming activities

Given the circumstances of being unable to either increase the tramming speed or reduce the tramming distances, a decision was made during July 2020 to optimize a refuelling channel as shown in Figure 4.11, referred to as channel one in the previous section. The main objective was to stop the refilling of Lube cassettes on surface, and rather have them refilled at the underground TMM workshop.

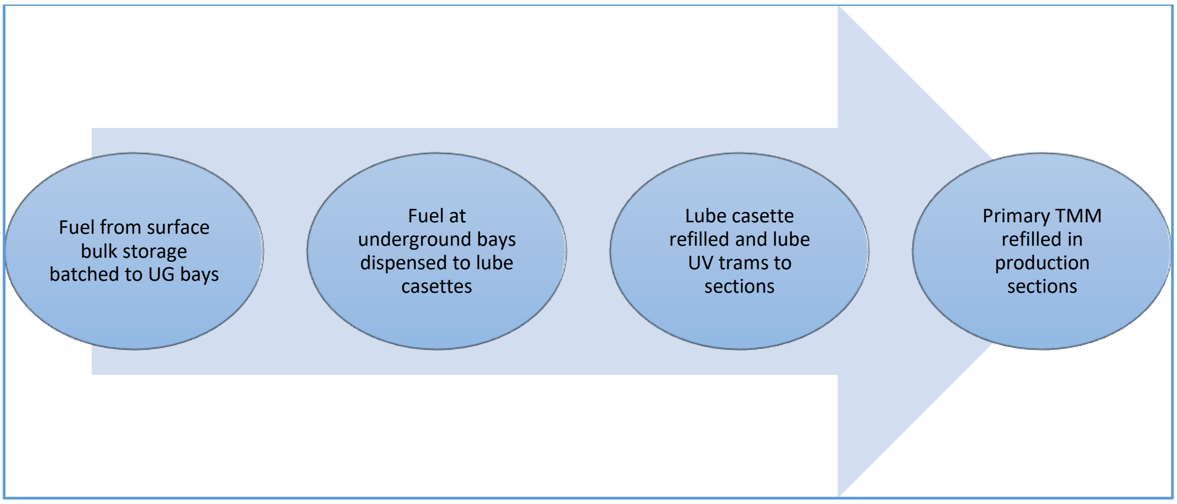

Figure 4.12: Underground TMM refueling channel one

Installing a pipeline from the surface bulk storage containers directly to the production sections is another option that was to be explored to eliminate the tramming constraint. With this option, primary production TMM would be refilled in their workplaces from satellite refilling bays. However, at the time of conducting the research, the project had just started, and hence no data was available for analysis.

4.5.3 Subordinate all activities to the decision made

Activities in the refuelling cycle were made subordinate to the decision in step two as the third phase of the TOC process. To optimize the refuelling, channel one, it was decided that Lube UV operators must refill and leave the lube cassettes at the underground refilling bay at the end of the shift. This was to ensure that the next shift will find all lube cassettes full and minimize the days at start of shift. The decision was communicated with the operators and supervisors on all shifts and was implemented during August 2020.

4.5.4 Elevate the constraint

Elevating the constraint involved monitoring compliance to the decision in step four (4) of the TOC implementation process. In figure 30, the dispensing of fuel from surface bulk storage directly to TMM from the surface bulk storage bay, and fuel dispensed by lube UVs to primary TMM underground is shown. The progress of the implementation of the decision to focus on using the lube UVs as the primary means to refill TMM in the underground sections, and thereby minimize tramming of primary TMM to and from TMM workshops. Consequently, the consumption of fuel by UVs increased in line with the decision as depicted in Figure 4.13, suggesting that the implementation of the decision was successful.

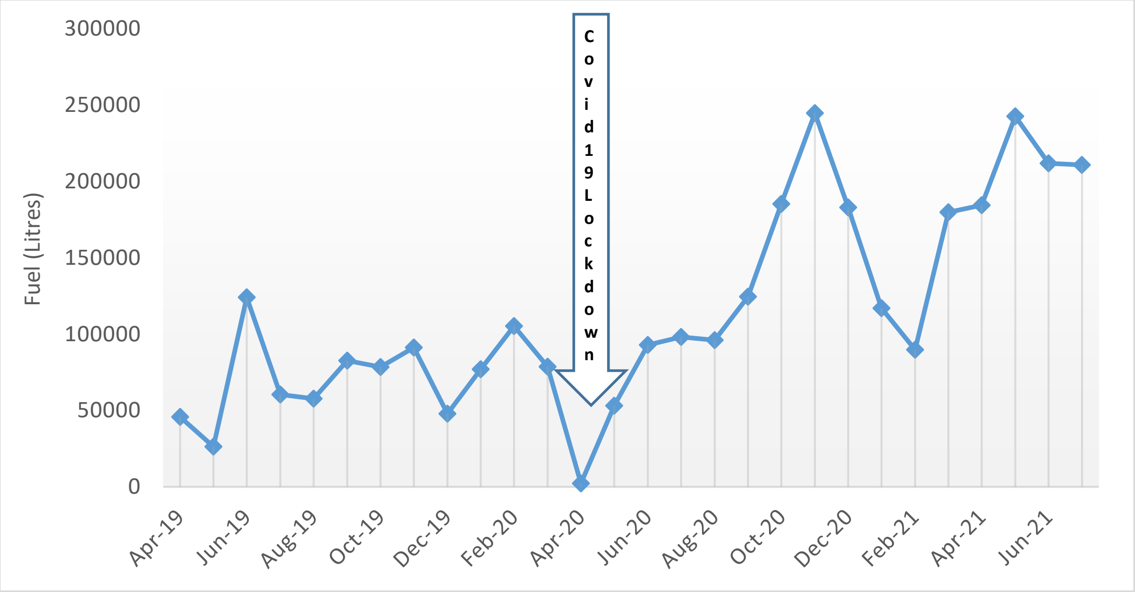

Figure 4.13: UV consumption of fuel per month

4.5.5 Provided the constraint is unlocked, restart the TOC process

If the constraint in step four (4) is broken, then the TOC process must be restarted with step one (1). This refers to step five (5) of the TOC process, however in this case the impact of the tramming constraint has only been reduced and remains the bottleneck of the refueling system. Therefore, another opportunity of reducing the refueling cycle must be considered, and it involves pumping fuel and lubricants to the satellite workshops in the working places. A project is currently underway at Bathopele mine to construct mini refueling stations in the strike sections.

4.6 Correlation Analysis

A correlation study was undertaken to determine if there is a relationship between fuel consumption and output at Bathopele mine. To apply Pearson coefficient of correlation, an assumption was made the relationship between the two variables; fuel consumed per month (*x*) and ore hoisted per month (*y*) is linear. The number of months (values) used is represented by *n*. The formula for calculating Pearson's coefficient of correlation will be applied according to the information contained in Table 4.2.

Table 4.2: Fuel consumed versus ore hoisted

Month (Y2021)	X	Y	XY	X^2	Y^2
Jan	295073,3	145638	42973886722	87068258274,36	21210427044,00
Feb	287757,4	244583	70380575502	82804338520,20	59820843889,00
Mar	319547,4	284496	90909959955	102110547237,71	80937974016,00
Apr	281846	235674	66423778917	79437178989,84	55542234276,00
May	338185,8	275020	93007864216	114369648849,07	75636000400,00
Jun	311566,8	265432	82699785586	97073839705,56	70454146624,00
Jul	343120,8	290428	99651893511	117731897117,47	84348423184,00
Sum	2177098	1741271	546047744410	680595708694,22	447950049433,00
Average	311013,9	248753	78006820630	97227958385	63992864204,71

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n \sum x^2 - (\sum x)^2][n \sum y^2 - (\sum y)^2]}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{[3.1]}$$

$$\boldsymbol{r} = \frac{7\,(546047744410) - (2177098)(1741271)}{\sqrt{[7\text{x}680595708694{,}22 - (2177098)^2][7\text{x}447950049433{,}00 - (1741271)^2}} = \frac{31417365469}{50300517192{,}36} = 0{,}624593289$$

The value of r is the correlation coefficient of the two variables. An r result of +0,625 as shown above suggests that there is a strong positive correlation between the fuel consumed and the production output from Bathopele mine. Therefore, as the fuel consumption increases and so does the production output. In order to test the significance of the correlation coefficient, an assumption that the sample is a representation of the population is necessary. In Figure 4.14, the regression line represents an estimate of the population. Lumen (2022) states that the y values and their associated x values represent a normal distribution about the regression line. The regression line is based on the following formula:

$y = mx + c$ …………………………………………………………………………….. *[4.2]*

- *y – dependent variable*
- *m – gradient*
- *x- independent variable*
- *c - constant*

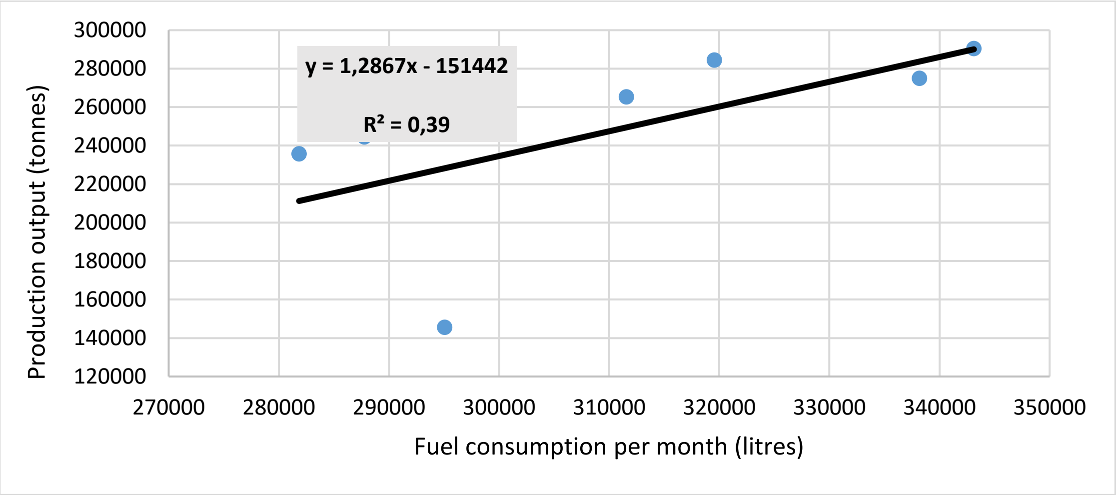

Figure 4.14: Fuel consumption versus output regression plot

To determine whether the result of r value is statistically significant or not, for two degrees of freedom (n - 2 = 7 - 2 = 5), therefore the critical value is 0.75 as per the critical values table contained in annexure B. Since r = 0.63 is less than 0.75, therefore r is not significant and the regression line may not be used for prediction of production output for known rate of fuel consumption, provided any other factors remain constant. The refueling infrastructure at Bathopele mine has sufficient storage capacity to meet the fuel requirements of the TMM fleet. With working places far from the fuel storage areas, tramming of UVs is a constraint on the refueling cycle. There is a directly proportional relationship between fuel consumed and the production output at Bathopele mine, and thus good fuel management will have a positive impact on the production performance of the operation.

Finally, this chapter provided an overview of Bathopele mine’s background, location, main infrastructure and refueling infrastructure. The refueling cycle was analyzed through time studies, and the Theory of Constraints tool was applied to determine the bottleneck of the refueling cycle. A correlation analysis was conducted based on historical data to determine the relationship between fuel consumption and production output at Bathopele mine.

5. BENEFITS OF USING IOT TECHNOLOGY FOR FUEL MANAGEMENT AT BATHOPELE MINE

This chapter will outline the benefits that were realised at Bathopele mine by IOT technology for fuel management. The main benefit achieved was the ability to track fuel consumption and more accurately determine the inventory requirements for Bathopele mine. Other benefits include tracking of fuel use per operational activity and per TMM. The data obtained from the IOT system is used for the inventory management, record keeping and diesel refund scheme applications. A model for near-real time and real time fuel management in underground bord and pillar trackless mine is drafted, and challenges and lesson obtained from this research study are outlined.

5.1 Fuel Consumption Tracking

The large TMM diesel fleet at Bathopele mine results in high consumption of fuel, and hence it is important to track the consumption of fuel monthly. In general, the consumption of fuel at Bathopele mine fluctuated in line with the rate of production from Aril 2019 to July 2021, whereby high utilization of TMM is required to achieve a high rate of production. In Figure 5.1, the total monthly consumption of fuel at Bathopele mine from April 2019 to July 2021 is shown.

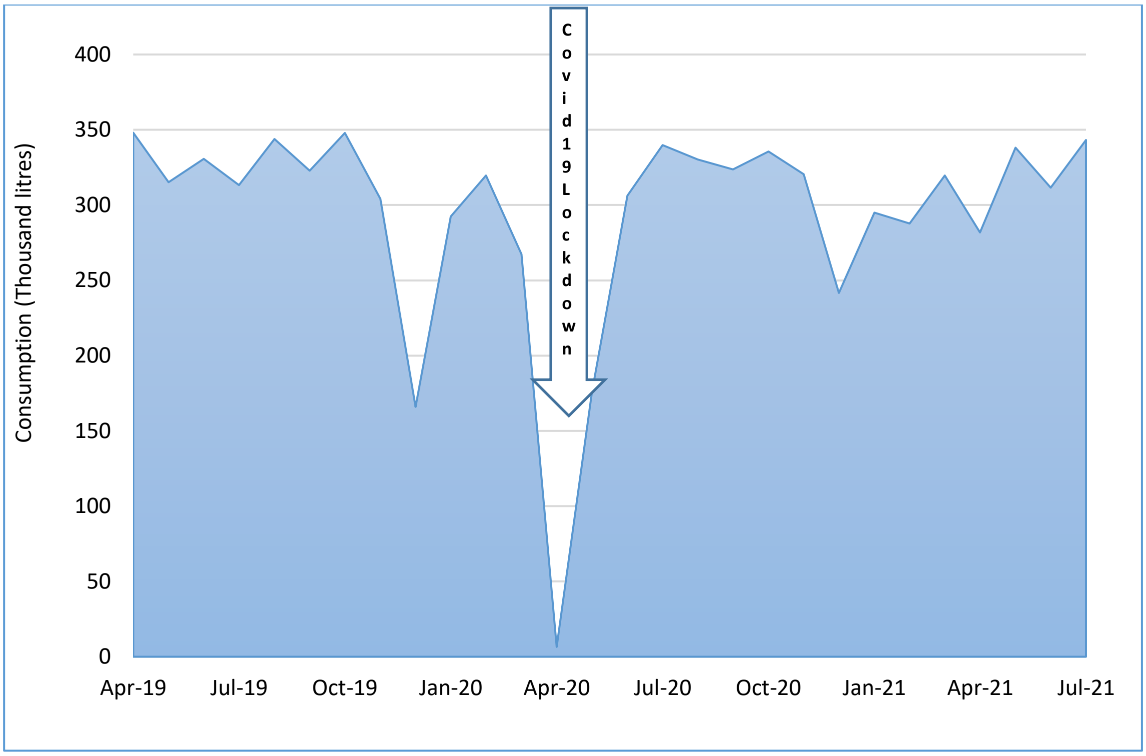

Figure 5.1: Fuel Consumption tracking at Bathopele mine

On average from April 2019 to July 2021, the fuel consumption was 299 259 litres per month. The fluctuations in fuel consumption are due to the varying production activity rates at the mine. From the 26th of March 2021, South African entered a national lockdown due to covid19 virus, and similarly mining operations were halted bar for the essential services of care and maintenance. Therefore, the consumption of fuel during this period dropped significantly. The consumption of fuel is generally low for the months of December and January due to the shutdown of the operations for the Christmas break, and the start-up of operations after the break. As the mines were allowed to gradually resume operations, the rate of consumption of fuel also rose gradually to reach pre lockdown levels by June 2020 when mines went back to full production.

5.1.1 The consumption of fuel per production activity

There are three main production activities at Bathopele mine which are conducted using a form of TMM, namely, transportation of men, transportation of material, explosives, fuel and lubricants, and the primary production activities. The transportation of men and material may be referred to as the secondary production activities. The first main production activity involves the transportation of men by personnel carriers and jeeps to and from surface to underground workplaces. Secondly the transportation of materials by UVs, Jeeps and personnel carriers, and in rare instances by LHDs, as well as the transportation of emulsion explosives, fuel and lubricants to and from bulk storage areas to primary production TMM in the workplaces represent the third main activity. The third activity comprises of primary production activities in the working places. These activities involve loading of ore by the LHDs, supporting of the hanging wall by the roof bolter and drilling of the panel (bord) to prepare for blasting. The average consumption of fuel (from April 2019 to July 2021) per production activity is shown in Figure 5.2.

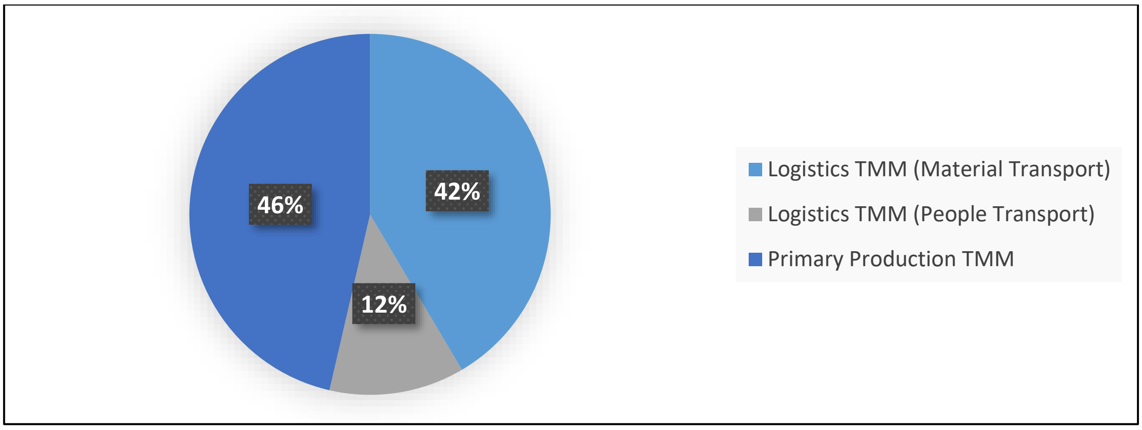

Figure 5.2: Average fuel consumption per main production activity (April 2019 to July 2021)

Primary production activities consume forty six percent (46%) of the total fuel consumed at Bathopele mine, and the transportation of material and people account for forty two percent (42%) and twelve percent (12%) respectively. Likewise, it can be concluded that secondary production activities account for eighty eight percent (88%) of the total fuel consumed at Bathopele mine.

5.1.2 The use of fuel per TMM type

Tracking the consumption of fuel by TMM type makes it possible for to identify TMM that consume the most fuel, and to investigate the root cause. Different TMM have different consumption rates according to their design characteristics. However, in the operating environment, there are other factors that may affect the fuel consumption rate of TMM such as the nature of operations undertaken, scheduled maintenance, type of fuel used, physical condition of the TMM and the way the TMM is being operated amongst others. According to Skawina (2019), several factors influence the efficiency of a vehicle, its fuel consumption and energy use; design of the vehicle, driver loading, hauling and dumping practices, scheduling practices, gradient and surface features of the road on which the vehicle travels and size and shape of the material being transported. Skawina (2019) suggests that the aggressive operation of equipment will have negative implications such as increased fuel consumption, poor turning, suboptimal tyre inflation, clogged filters amongst others. This is illustrated in Figure 5.3, with increased consumption and poor turning accounting for seventy percent (70%) of the impact.

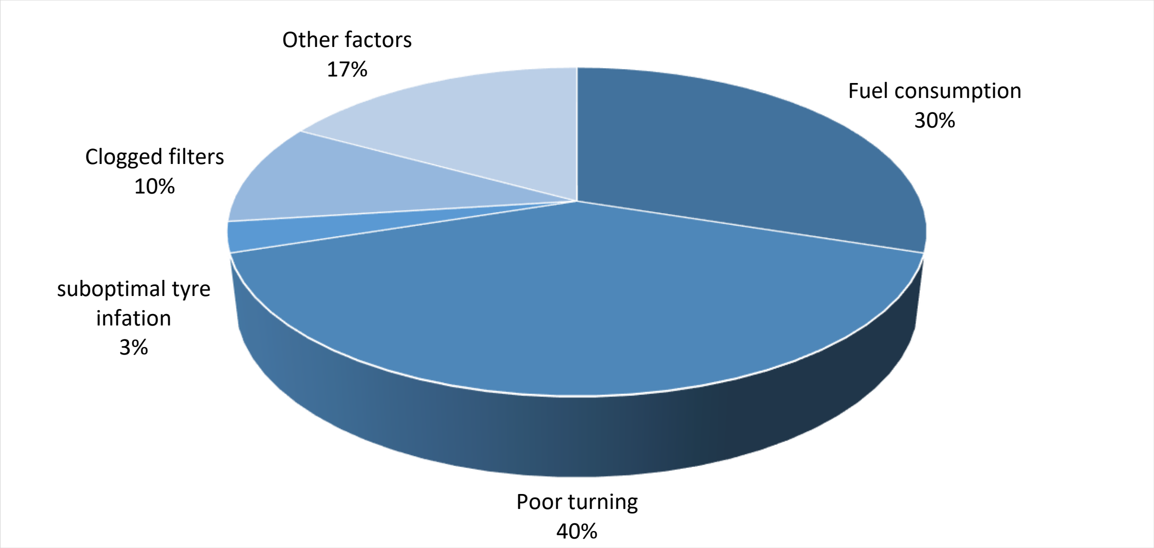

Figure 5.3: Impact of aggressive operation of equipment (Skawina, 2019)

From April 2019 to August 2020, lube cassettes accounted for the most fuel consumed, followed by Jeeps and PCs, UVs, primary TMM, Other TMM and no records in that order as shown in Figure 5.4. However, the consumption of fuel by the lube cassettes has been on the decline in line with the decision taken during August 2020, to refill and leave lube cassettes underground at the TMM workshop (refer to section 4.3.3). Consequently, the consumption of fuel by UVs increased because of the recording of the consumption of the lube cassettes using the number of the UV that is transporting it. Thus, the quantity of fuel consumed includes the quantity in the lube cassette being transported by the UV.

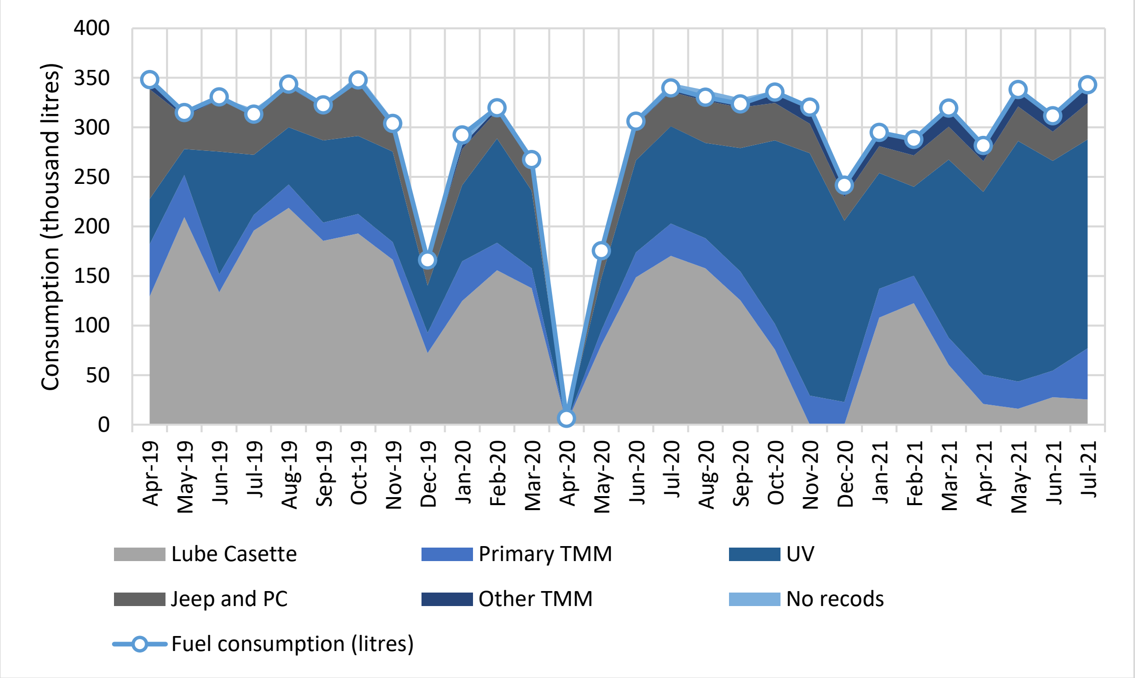

Figure 5.4: Fuel consumption per TMM type (April 2019 to July 2021)

Fuel consumption by jeeps, personnel carriers, primary production TMM and other TMM has remained the same on average and fluctuate proportional to production activity at Bathopele mine. Primary production TMM consumption rates also differ depending on the type of operation equipment is used for. An LHD which transports ore from the blasted panel or end to the tipping point travels more distance compared to rigs and bolters that perform drilling activities from a stationary position. The average consumption of primary TMM from January 2021 to June 2021 is shown in Figure 5.5.

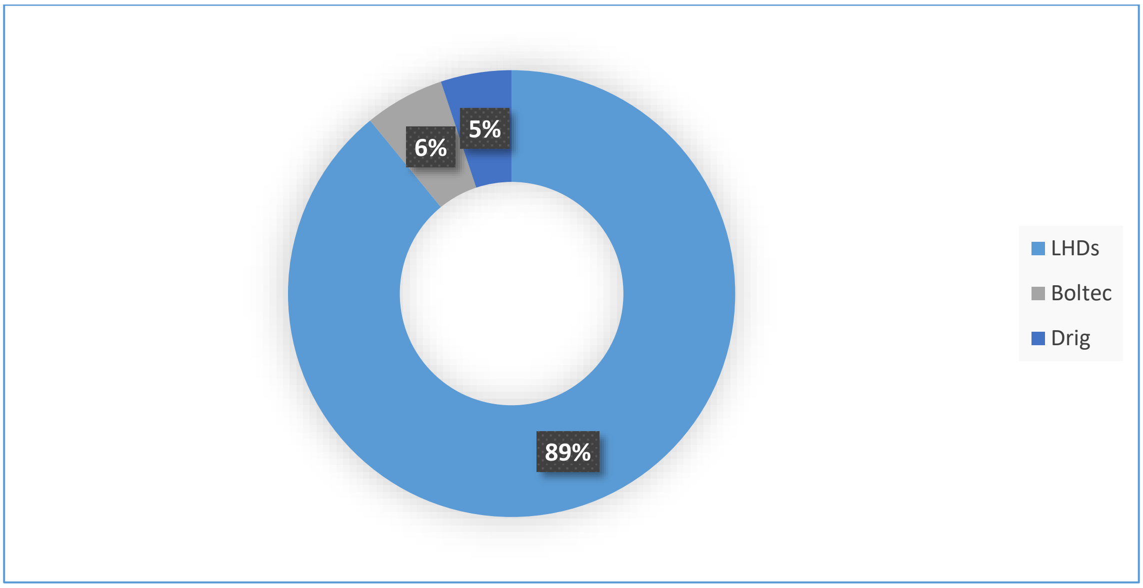

Figure 5.5: Six months average consumption of primary production TMM at Bathopele mine

Unsurprisingly, LHDs account for eighty nine percent (89%) of the primary production TMM fuel consumption, followed by BCs with six percent (6%) and DRs at five percent (5%).

5.1.3 TMM ranking by consumption by specific number

Fuel consumption by a specific TMM is tracked through the refuelling card used by the operator when refuelling at the storage bay. TMM with the highest consumption rates of consumption are flagged and prioritized for maintenance and root-cause analysis is initiated. The breakdown history, age, scheduled maintenance track record, and working place conditions of the TMM as well as operator factor are all considered when undertaking a root-cause analysis exercise.

5.1.4 Refueling cards

Refuelling cards are issued to each licenced operator of TMM at Bathopele mine and are used to access fuel either from the refuelling bay or from the Lube UV. A typical refuelling card contains details of the operator such as their name and surname, photo, industry number and details of the type of TMM they are licensed to use. When the operator scans the refuelling card on the RFID reader at the refuelling bay, the details of the operator and the amount of fuel dispensed into the TMM is recorded. Therefore, the operators may be ranked according to the amount of fuel they use. In Figure 5.6, LHDs of one OEM were ranked according to their diesel consumption from the bulk surface storage facility during the month of April 2021. The fuel consumption of the top ranked LHD (LHD1) is almost four times the consumption of the lowest ranked LHD (LHD 20). Although there are a few reasons for the varying consumption rates, such as the nature of operations, maintenance activities, and LHD on surface daily refuelling from the bulk storage facility, ranking of TMM by consumption is still a useful tool to flag TMM with the highest consumption for maintenance interventions.

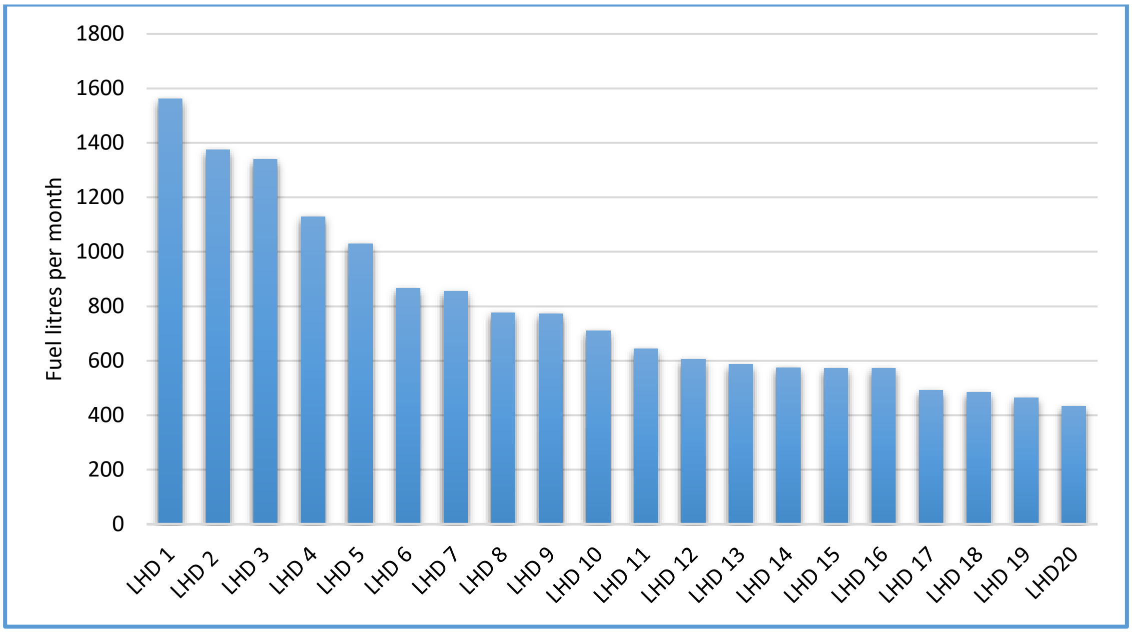

Figure 5.6: Top twenty LHDs by fuel consumption for April 2021

While most of the LHDs are used for primary production activities, other LHDs are used for roadway maintenance, strike belt extensions and sweepings activities. Primary production LHDs are parked underground and refilled by Lube UVs underground, thus fuel consumption recorded under lube cassette, and other LHDs are parked on surface and refilled from the bulk storage areas and captured on the IOT system. Provided through maintenance interventions, the fuel consumption of the top twenty (20) LHDs may be reduced by fifty percent (50%), Bathopele mine would save approximately seven thousand nine hundred and twenty-three (7923) liters of fuel monthly, and ninety-five thousand and seventy nine (95079) litres of fuel per annum. The average wholesale fuel (diesel) price in April 2021 was fourteen rand and seventy cents (R14.70), and thus the annul fuel saving above would have been approximately R 1,407,175.42 only for LHDs that refuelled on surface.

5.2 Inventory Management

The large amount of fuel consumed during operations at Bathopele mine warrants a good inventory management system, which ensures that enough fuel is stored at the mine. Shortages of fuel would lead to great production loss, and a system of monitoring of fuel levels in required to prevent this as well as possible theft of fuel.

5.2.1 Fuel stocks management

It was established in section 5.1 that the average fuel consumption over the period of the research study was 299 259 litres per month. Therefore, considering that during Sunday mornings only maintenance activities are undertaken at Bathopele mine, the average daily fuel consumption over a thirty (30) day period will be equal to 9975,3 litres [$(\frac{299\ 259}{30}) =$ 9975,3 litres)]. The lead time to delivery of fuel at Bathopele mine is seven days, and therefore current practice is to maintain stock levels for fourteen days as per the maximum storage capacity on site, and to accommodate any supply chain disruptions.

In Table 5.1, a typical shift report on fuel balancing from the IOT system is produced at Bathopele mine. The information on the report is generated automatically by the system and is validated by the checklist of the diesel bay attendant who observes and records information from the fuel gauges on the storage tanks.

Table 5.1: Shift fuel balance report at Bathopele mine

PROGRESSIVE DAILY AREA BALANCE REPORT – 30 April 2021							
Area	**Opening**	**Receiving**	**Consumption**	**Batching East**	**Batching Central**	**Closing litres**	**Variance litres**
Surface	62844	296435	88632,75	93962	95836	79980	-868,25
East 7W	4000	93962	96120,01	0	0	2400	558,01
East 13W	1600	0	249,19	0	0	1356	5,19
Central	3300	95836	96844,78	0	0	1199	-1092,22
East Transfer Tank	500	0	0	0	0	500	0
Central Transfer Tank	500	0	0	0	0	500	0
Total	**72744**	296435	**281846,73**	**0**	**0**	**85935**	-1397,27

The fuel balancing report also provides the amount of fuel that was dispensed by was not recorded due to teething technical problems associated with the implementation of the IOT-based fuel management system. Between the months of July 2019 and October 2020, a total of approximately 30000 litres of fuel showed no records on the output reports, and the use of the fuel balancing report assisted in determining that the cause of this discrepancy which was due to the system duplicating data of the users of the system. As shown in Figure 5.7, the quantities not recorded have reduced significantly with time as the initial challenges were being overcome, and thus improving the accuracy of the fuel inventory records.

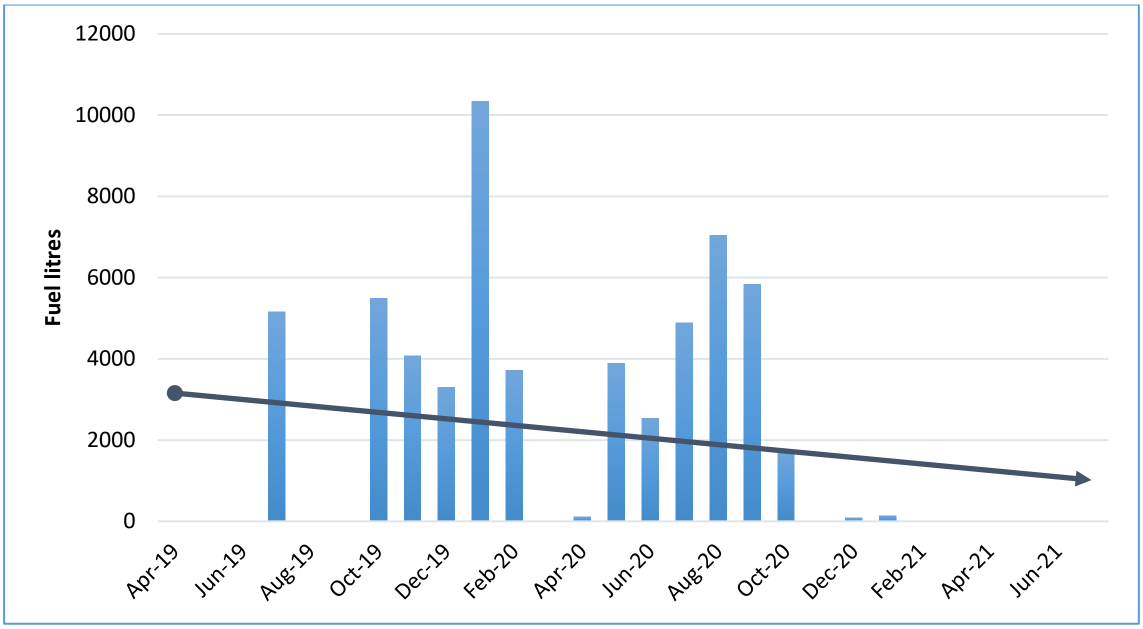

Figure 5.7: Quantities of fuel not recorded with records of TMM

6.2.2 Diesel refund scheme data

To apply for fuel rebates from the SARS it is imperative to ensure that the application meets all the requirements. According to Sars (2017), qualifying enterprises must maintain records fuel consumption records in supporting documentation in the form of purchase and sales invoices and logbooks. Sars (2021) announced increases from 07 April 2021, resulting in general fuel levy equal to three hundred and seventy cents per litre (370 cents/litre) and RAF levy of two hundred and eighteen cents per litre (218 cents/litre). Using the average fuel consumption of Bathopele mine, and assuming ninety percent (90%) of fuel consumed fuel qualifies for DRS, an example of a diesel refund calculation is contained in Table 5.2

Table 5.2: An example of a DRS calculation for April 2021

Tax Return	**Amounts**
40% of general fuel levy per litre	148 cents
100% of RAF levy per litre	218 cents
Total refund per litre 80% of qualifying fuel consumption	366 cents
Total litres consumed	299 259.00
Non eligible litres (10%)	29 925.90
Eligible litres	269 333.10
80% of eligible litres	215 466.48
Amount refundable (in cents) = 366 c/l x 215 466.48l	78 860 731.68
Total refundable (in Rands)	**788 607.32**

Therefore, a mine with a fleet that has an average fuel consumption equal to Bathopele mine was eligible for a diesel refund of seven hundred and eighty-eight thousand, six hundred and seven rand, and thirty-two cents per month (R788 607.32 per month or approximately R9.46 million per annum).

5.3 A Model for Near Real-Time or Real Time Fuel Management System

Due to the dynamic nature of the mining operations, there is a need for prompt response and data-based decision making to address issues arising during production activities. The principle of the use of real-time information management systems is to ensure that “the right information is available to the right person all the time” (Mandela Mining Precinct, 2023). The delay in the availability of information results late reactions to challenges encountered and lost opportunities to improve operations. Real time information management system architectures and standards are still in development stage in the mining industry, and there is work to be done until such systems can be adopted holistically. The complexity of real time information management systems requires cooperation of the developers of the technology, the buying organization and the end users (operations) to ensure that the final product is fit for purpose.

Based on the lessons of this research study, a model of an IOT-based near real-time or real-time fuel management system at an underground mechanised bord and pillar mine can be established. As shown in Figure 5.8, an IOT-based fuel management system has four main parts including the IOT infrastructure, IOT components, IOT management platform and the command centre.

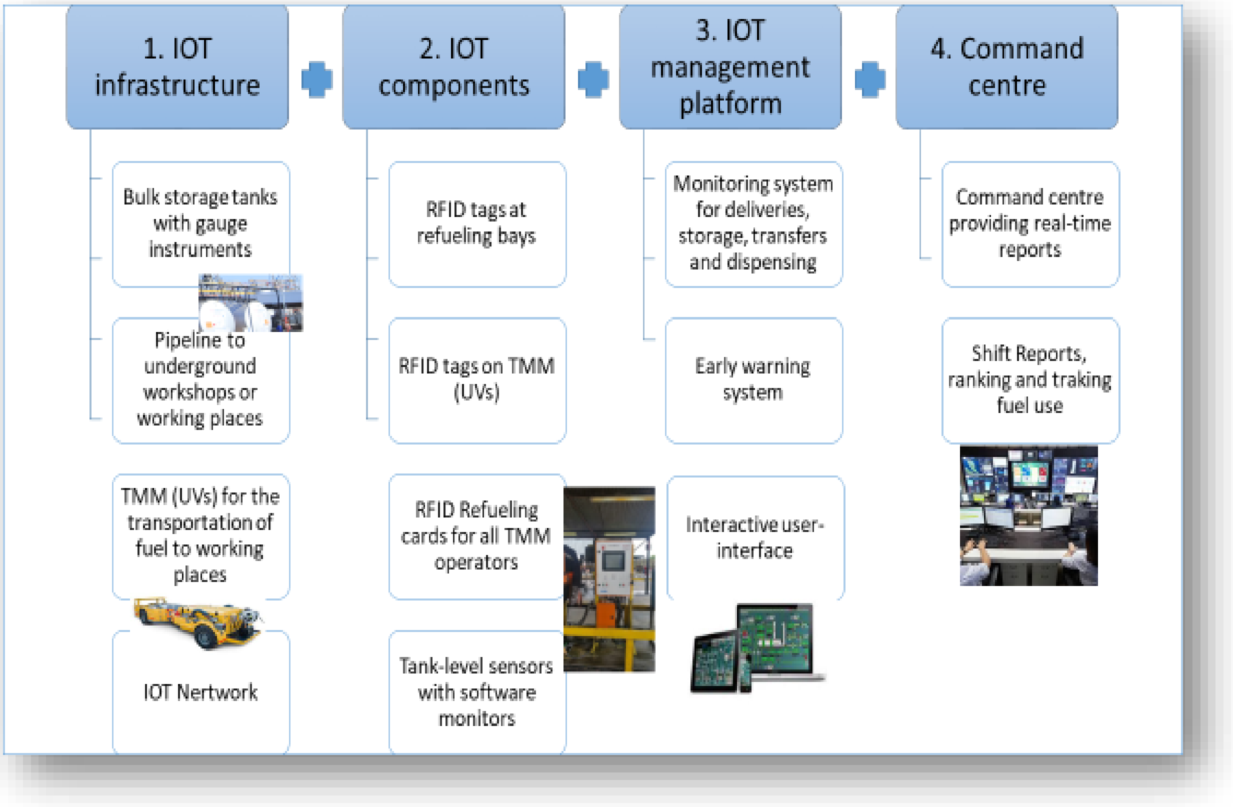

Figure 5.8: Model of an IOT-based real time or near real time fuel management system for underground mechanized bord and pillar mine

An IOT-based fuel management system will fulfil six main functions as shown in Figure 5.9. These functions include inventory management, efficient fuel delivery, consumption tracking, and maintenance scheduling and record keeping.

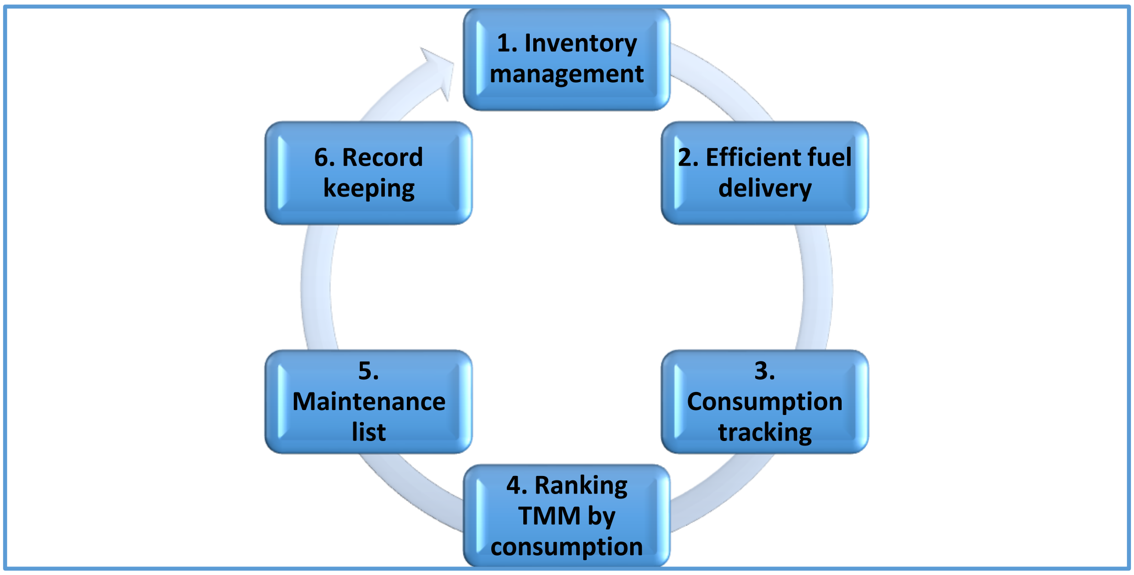

Figure 5.9: Main functions of an IOT-based real time or near real time fuel management system for an underground mechanized bord and pillar mine

In this chapter, the main benefits that were realised through the migration to IOT-based fuel management system at Bathopele mine were discussed, namely, fuel consumption tracking, fuel inventory management, and ease of access to data for diesel refund scheme application. A model for a real time or near real time IOT-based fuel management system for an underground mechanised bord and pillar mine was formulated based on the findings of the research. This application of this model is subject to further trials and research development.

In this chapter, the main findings of the research are discussed. Fuel management data obtained from the IOT-based fuel management system is examined. Monthly fuel consumption by different TMM types and different production activities are analysed, and TMM of the same type are ranked based on their consumption. Fuel inventory reports derived from the system indicate that Bathopele mine with an annual fuel consumption of approximately three and a half (~3.59) litres is eligible to apply for an annual fuel rebate from SARS of approximately nine and a half million rands (R9,46m). Based on the research results, a proposed model for an IOT-based fuel management system is also developed.

6. CONCLUSION AND RECOMMENDATIONS

This chapter will summarize the key findings of the research study and give recommendations for future research and projects.

6.1 Conclusion

Several change forces have let the mining industry to embrace new technologies such as IOT and seek opportunities to improve operations. The IOT technologies have several capabilities with the potential to improve operations are applicable to various industries including mining. The introduction of IOT-based fuel management in trackless underground bord and pillar mines unlocks several benefits for the effective management of fuel. To implement IOT-based fuel management various infrastructure requirements must be met. It was also determined that fuel consumption is directly proportional to production output, and thus an effective fuel management system will have a positive impact on production output.

Application of the TOC determined that due to increased distance from the workings, the tramming of UVs to the workplaces to supply fuel is a major constraint, and that interventions of installing refuelling infrastructure closer to the workings will assist in overcoming this challenge. Most of the fuel is consumed during the process of transporting people and materials to underground working places due to the long distance to working places from surface. Different TMM types have different consumption rates and were ranked according to type and prioritized for maintenance and operators were retrained. The availability of IOT-based fuel management system improved the fuel inventory monitoring for SARS rebate applications. A proposed model for near real time or real time fuel management in trackless underground bord and pillar mines was developed, and can be further developed for real-time fuel consumption monitoring and short interval controls.

Challenges facing the mining industry in line with the global shift towards green energy and reduction of emissions, suggest that operations such as Bathopele mine with large diesel-powered TMM fleet must explore ways of reducing emissions in the short term, and conduct further research on the replacement of diesel fleets for the long run.

6.2 Recommendations

From the findings of the research study, the following recommendations are made:

- The use of IOT fuel management systems must include other consumable lubricants such as engine and hydraulic oil to provide a holistic view of the TMM state of being.
- Underground trackless mining operations using diesel engine powered TMM must conduct feasibility studies to explore options of extending their

fuel pipeline to underground working places to reduce the downtime due to travelling distances of TMM.

6.3 Future research work

Further research is required to determine an optimal model for real-time IOT-based fuel management system for underground trackless bord and pillar mining operations. Such a model should be supported by system based short interval controls to ensure the effectiveness of the fuel management system. Research into alternative fuel sources such as battery and fuel cell for TMM in underground operations, and associated infrastructure constrains is required to determine the optimal energy source mix for the current and future ESG-based mining practices.

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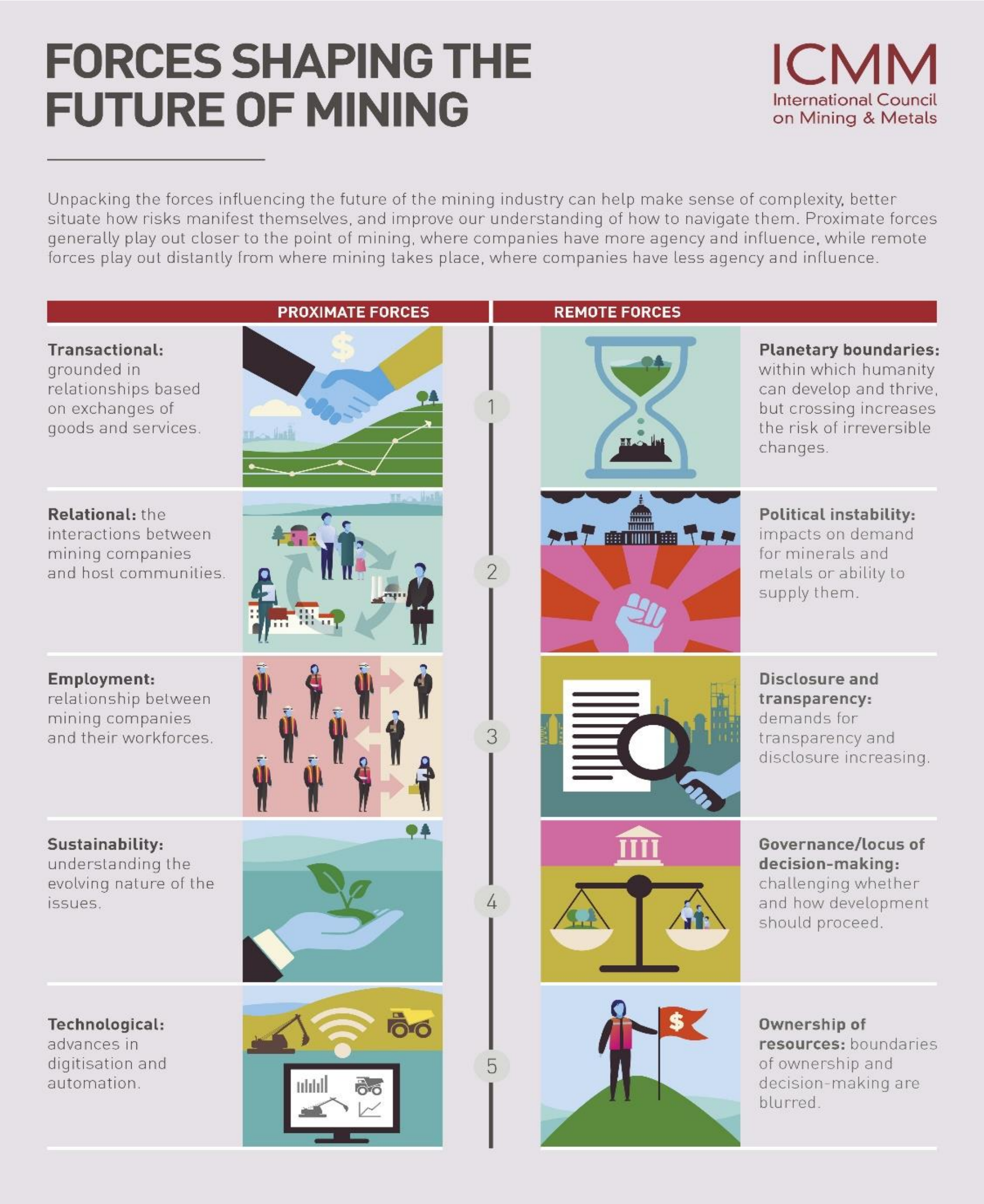
APPENDICES

A. Chapter 1

A.1 Fourth Industrial Revolution – Forces impacting the mining sector.

https://www.weforum.org/agenda/2021/05/global-forces-shaping-future-mining-industry/ (Accessed 05/06/2022 at 16h40)



FORCES SHAPING THE FUTURE OF MINING

ICMM
International Council on Mining & Metals

Unpacking the forces influencing the future of the mining industry can help make sense of complexity, better situate how risks manifest themselves, and improve our understanding of how to navigate them. Proximate forces generally play out closer to the point of mining, where companies have more agency and influence, while remote forces play out distantly from where mining takes place, where companies have less agency and influence.

PROXIMATE FORCES		REMOTE FORCES
Transactional: grounded in relationships based on exchanges of goods and services.	1	**Planetary boundaries:** within which humanity can develop and thrive, but crossing increases the risk of irreversible changes.
Relational: the interactions between mining companies and host communities.	2	**Political instability:** impacts on demand for minerals and metals or ability to supply them.
Employment: relationship between mining companies and their workforces.	3	**Disclosure and transparency:** demands for transparency and disclosure increasing.
Sustainability: understanding the evolving nature of the issues.	4	**Governance/locus of decision-making:** challenging whether and how development should proceed.
Technological: advances in digitisation and automation.	5	**Ownership of resources:** boundaries of ownership and decision-making are blurred.

A.2 Type of Fermel TMM used at Bathopele mine for secondary production activities. https://www.fermel.co.za/products/ (Accessed 05/06/2022 at 16h48)

Cassette handler/Utility vehicle

Shuttle 18 man LP

NewGen mini UV LP (Similar to a Jeep)

MED - Grader 12700

A.3 Type of Epiroc TMM used at Bathopele mine for primary production activities. https://www.epiroc.com/en-za/products/loaders-and-trucks/diesel-loaders/scooptram-st7lp (Accessed 05/06/2022 at 16h57)

LHD – ST700

https://www.epiroc.com/en-za/products/drill-rigs/face-drill-rigs/boomer-s1l
(Accessed 05/06/2022 at 17h05)

Drill Rig – S1

https://www.epiroc.com/en-za/products/rock-reinforcement/rock-bolting-rigs/boltec-sl (Accessed 05/06/2022 at 17h09)

Boltec – SL

B. Chapter 2

B.1 Sample Coefficient of Corellation Table with 95% critical values

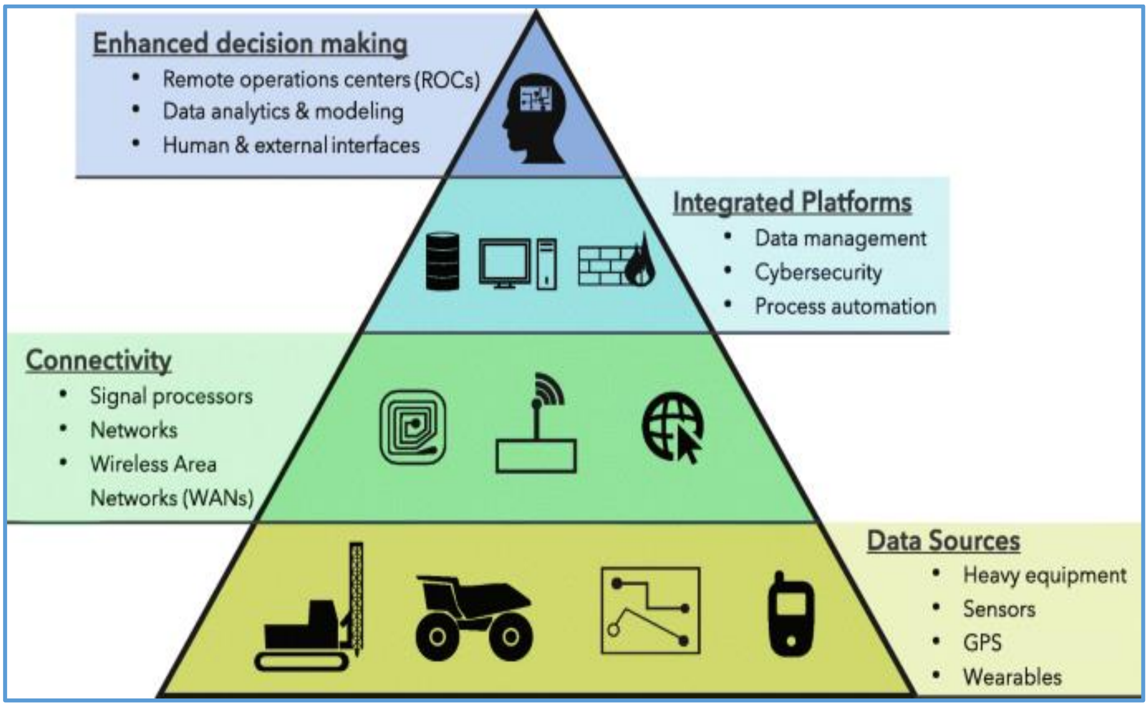
(Lumen, 2022).

95% Critical Values of the Sample Correlation Coefficient Table	
Degrees of freedom: n -2	**Critical values: (+ and -)**
1	0.997
2	0.950
3	0.878
4	0.811
5	0.754
6	0.707
7	0.666
8	0.632
9	0.602
10	0.574
11	0.555
12	0.532
13	0.514
14	0.497
15	0.482
16	0.468
17	0.456
18	0.444
19	0.433
20	0.423
21	0.413
22	0.404
23	0.396
24	0.388
25	0.381
26	0.374
27	0.367
28	0.361
29	0.355
30	0.349
40	0.304
50	0.273
60	0.250
70	0.232
80	0.217
90	0.205
100	0.195

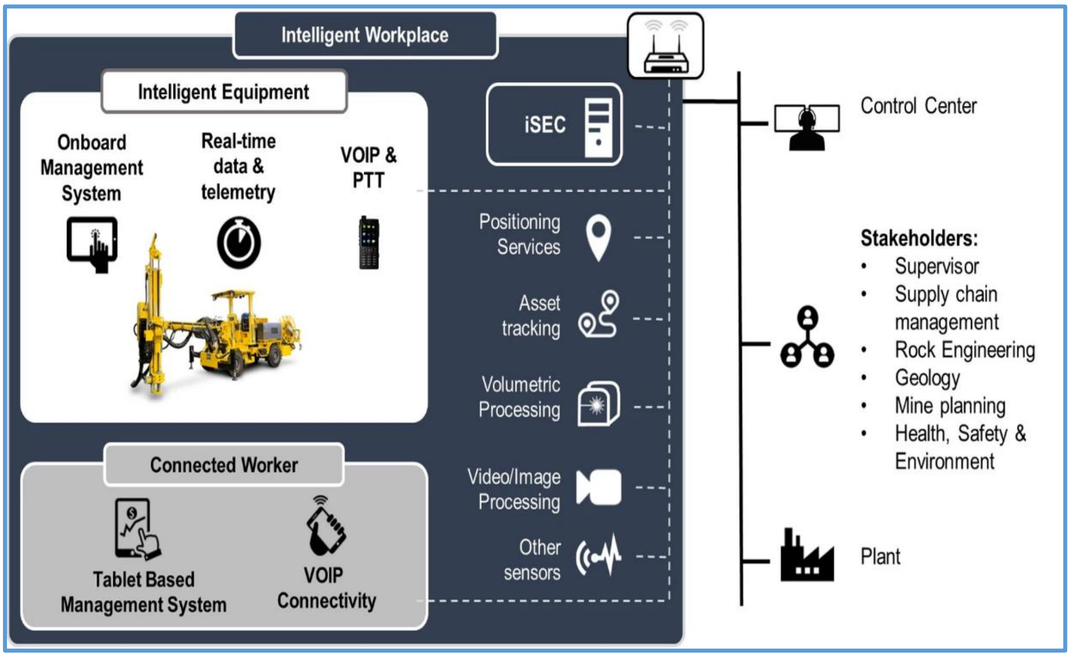
C. Chapter 3

C.1 Components of digital transformation in the mining sector.

https://link.springer.com/article/10.1007/s42461-019-00103-w (Accessed 05/06/2022 at 18h04)



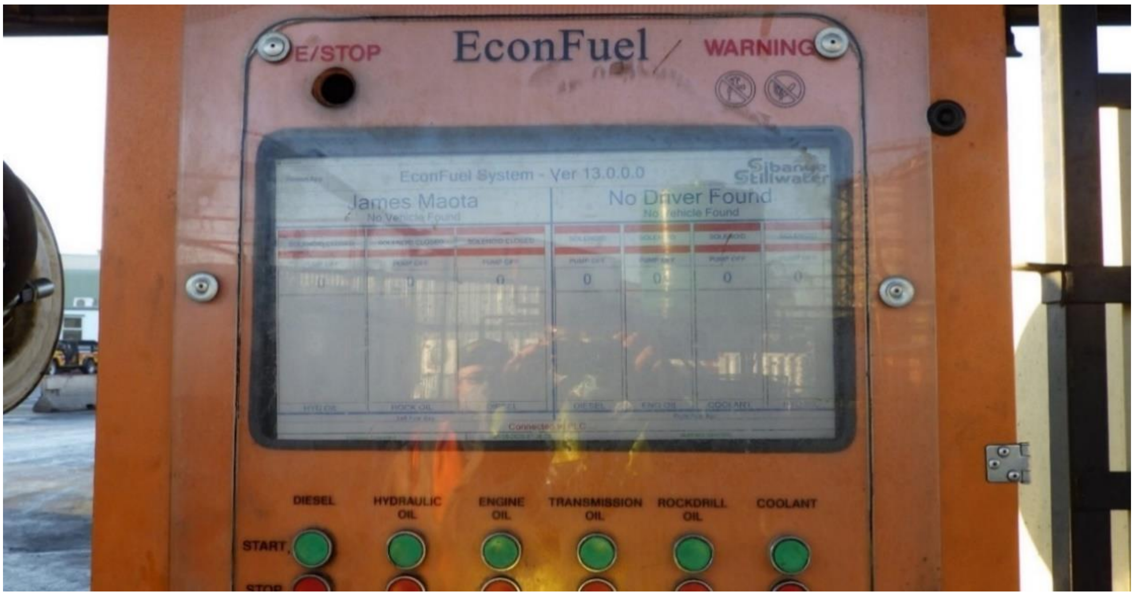
C.2 Illustration of the use of short interval control in the mining sector. https://www.minerp.com/single-post/2018/09/05/short-interval-control-40-for-mining (Accessed 05/06/2022 at 18h14)



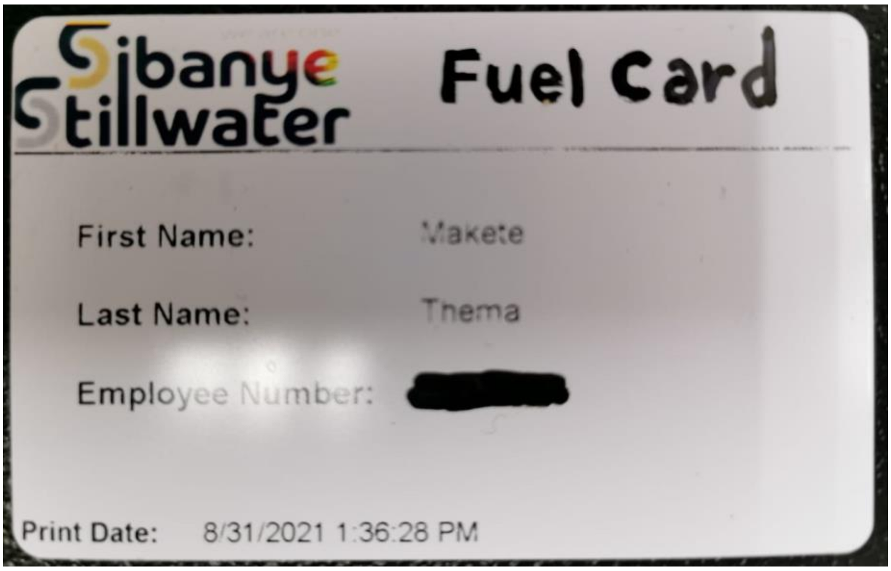
D. Chapter 4

D.1 Bulk fuel and lubricants storage infrastructure at Bathopele mine.

D.2 EconFuel management system (by Afrigle) in use at Bathopele mine



D.3 TMM operator's RFID fuel card at Bathopele mine



Sibanye Stillwater **Fuel Card**

First Name: Makete

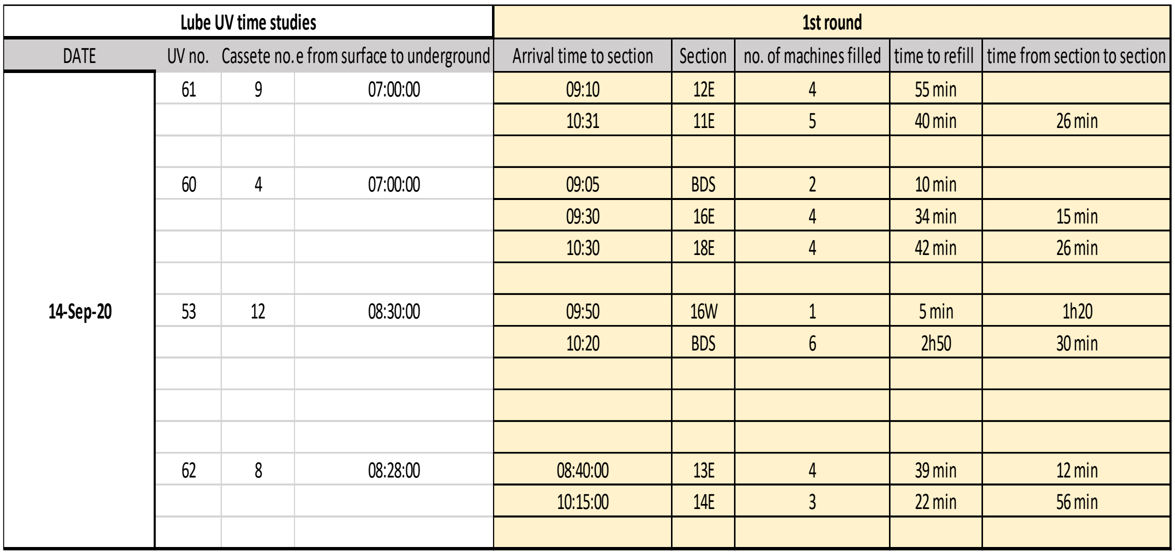
Last Name: Thema

Employee Number: [redacted]

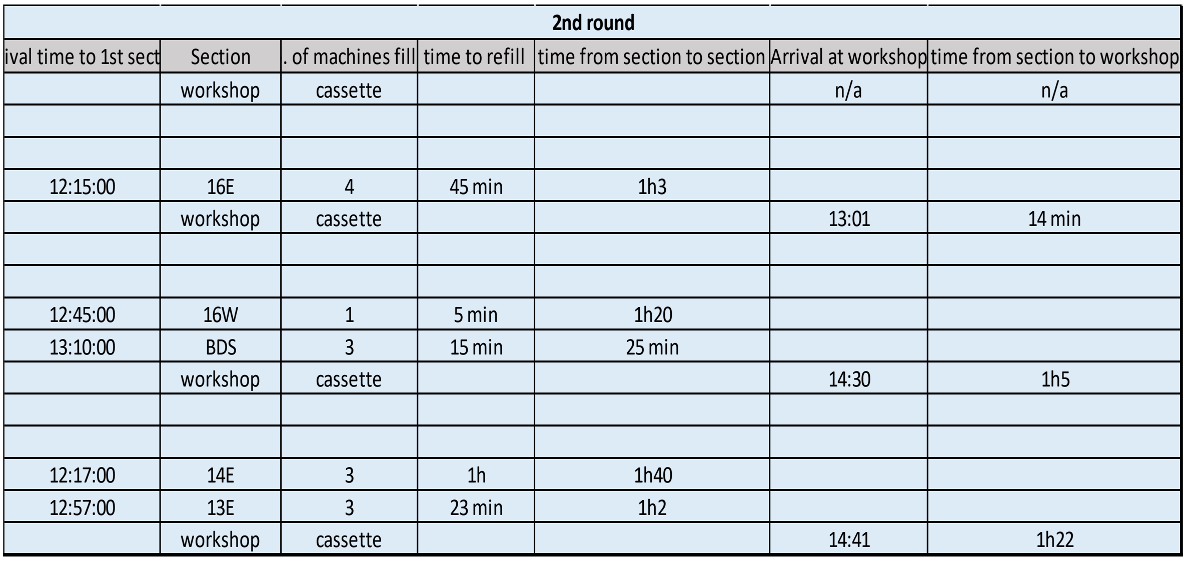
Print Date: 8/31/2021 1:36:28 PM

E. Chapter 5

E.1 Example of a lube UV report (14/09/2020) indicating time studies on the refueling cycle time.



Lube UV time studies				1st round				
DATE	UV no.	Cassete no.	e from surface to underground	Arrival time to section	Section	no. of machines filled	time to refill	time from section to section
14-Sep-20	61	9	07:00:00	09:10	12E	4	55 min	
				10:31	11E	5	40 min	26 min
	60	4	07:00:00	09:05	BDS	2	10 min	
				09:30	16E	4	34 min	15 min
				10:30	18E	4	42 min	26 min
	53	12	08:30:00	09:50	16W	1	5 min	1h20
				10:20	BDS	6	2h50	30 min
	62	8	08:28:00	08:40:00	13E	4	39 min	12 min
				10:15:00	14E	3	22 min	56 min



2nd round						
ival time to 1st sect	Section	. of machines fill	time to refill	time from section to section	Arrival at workshop	time from section to workshop
	workshop	cassette			n/a	n/a
12:15:00	16E	4	45 min	1h3		
	workshop	cassette			13:01	14 min
12:45:00	16W	1	5 min	1h20		
13:10:00	BDS	3	15 min	25 min		
	workshop	cassette			14:30	1h5
12:17:00	14E	3	1h	1h40		
12:57:00	13E	3	23 min	1h2		
	workshop	cassette			14:41	1h22