Optimizing Open-Cast Mining Drilling Processes Through Digital Mining

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KEYWORDS

Digital Mining, Open-Cast Mining Drilling, Automation, Digitalization, Operational Consistency

DECLARATION

I, _________Nomcebo Sinodumo Mlotshwa_____________________, declare that this research report is my own work except as indicated in the references and acknowledgements. It is submitted in partial fulfilment of the requirements for the degree of Master of Management in the field of Digital Business at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other university.

Name: Signature: N. Mlotshwa

Signed at …Centurion…………………………………………………

On the …27………………………….day of …February……………………… 2025…..

DEDICATION & ACKNOWLEDGEMENT

Dedication

I dedicate this dissertation to everyone who supported, motivated, and encouraged me through this time. To my children and admirers, may this be an indication that anything and everything is possible and may it inspire you to always push and test your potential and dare to dream.

Acknowledgement

Thank you to my supervisor, colleagues, and friends for their contribution and guidance throughout this journey.

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IoT	Internet of Things
AI	Artificial Intelligence
QA/QC	Quality Assurance/Quality Control
ADS	Autonomous Drilling System
AHS	Autonomous Haulage Systems
GDP	Gross Domestic Product
US	United States
UAV	Unmanned Aerial Vehicles
OEM	Original Equipment Manufacturer
GIS	Geographic Information Systems
AR	Augmented Reality
VR	Virtual Reality
RCS	Rig Control System
HNS	Hole Navigation System
Auto RHS	Auto Rod Handling System
WOB	Weight on Bit
RPM	Rotations Per Minute
TOE	Technology-Organization-Environment
DOI	Diffusion of Innovation
ROI	Return on Investment
ML	Machine Learning
MHSA	Mine Health and Safety Act

CHAPTER 1. INTRODUCTION

1.1 Statement of purpose

This quantitative study explores the potential of digitalization and automation in enhancing operational consistency of open-cast mining drilling processes in the South African mining sector. This study aims to evaluate the digital landscape in the mining industry, delve into the taxonomy of factors in drilling processes to understand the key factors influencing its performance and quality of its outcomes, and explore the barriers to autonomous drilling with an aim to uncover the primary obstacles that hinder the adoption and implementation of autonomous drilling. The insights gained from this research study will contribute to the development of a framework that facilitates the adoption and implementation of autonomous drilling in open-cast mining operations, thereby enabling the mining industry to fully harness the transformative potential of autonomous technology.

1.2 Background of the study

According to Hussain et al. (2021), mining is a pivotal activity in our nation's development, involving the extraction of substantial amounts of overburden to reach required materials. Drilling, a critical process in open-cast mining, is employed to create blast holes on the surface for explosives, which are essential for fragmenting the rock mass. The current research is geared towards enhancing these drilling processes by incorporating digital mining technologies. The primary focus is on augmenting planning efficiency and optimizing resource utilization.

Digital mining involves the application of digital technologies such as Internet of Things (IoT), Artificial Intelligence (AI), and big data-powered analytics to enhance various mining processes (Stefanini Group, 2019). By leveraging these technologies, mining operations can benefit in that it can use these emerging technologies to mitigate variability caused by external forces instead of leaving situations to chance (Stefanini Group, 2019). Although, in the opinion of Rogers et al. (2019), technology alone can never give the organization an edge over its competitors or provide a step change, which is true because the role of human resources, politics, to name a few, has a considerable impact on the industry's sustainable development.

In the context of this research project, planning efficiency indicates the ability to design and execute mining operations with minimal disturbance and maximum productivity. This includes accurate activity scheduling, resource allocation, and real-time monitoring of operations. The deployment of such capability enables for the optimization of the whole supply chain instead of local silos (Stefanini Group, 2019).

Automation is becoming increasingly integrated into mining processes, shifting bottlenecks from tasks dependent on human intervention, yet not completely eliminating human involvement, as pointed out by (Kansake et al., 2019). These authors further highlight that with the advancement of technology, the importance of effective data management and analytics is growing, becoming crucial for optimizing operations and establishing strong feedback mechanisms. However, challenges in technology deployment and implementation persist. Hence, this research is primarily aimed at South African mining companies and scholars specializing in mining engineering & technology. It also, to a certain extent, caters to policymakers and other regulatory entities interested in sustainable mining practices. By connecting the dots between conventional mining approaches and modern digital innovations, this research seeks to offer significant perspectives through developing a structure that offers strategic directions for mining companies to smoothly transition to and incorporate autonomous drilling systems in surface mining operations.

1.3 Research Problem

The mining industry plays a pivotal role in global resource extraction, utilizing sophisticated machinery and large workforces to cater to the increasing demands for diverse mineral resources. As highlighted by Kansake et al. (2019) mining significantly contributes to the sustenance and expansion of both global and national economies by providing raw materials, creating jobs, generating revenues, and earning foreign exchange.

While acknowledging the benefits of the mining industry, it is important to recognize that mining environments are inherently hazardous. The sector is reported to have the second highest fatality rate among the private sector in the United States (US). Furthermore, human involvement is cited as a significant factor in surface mine accidents, with nearly 85% of all mining accidents attributes to human errors.

The evolution of the mining sector is such that to remain competitive in global markets over time, the industry must improve and maintain operational efficiencies by building the mine of the future (Fisher & Schnittger, 2012). According to Fisher & Schnittger, (2012), the costs and associated wider challenges of automation in the mining sector are substantial, but they are potentially outweighed by the benefits they can deliver. Some of the greatest benefits noted by Brown, (2014) and Lovells (2018) include improved operational and equipment efficiencies, safety, and decreased environmental impact and expenditure. Yet, despite these known benefits of digitalization and automation, the sector still faces significant critics and/or challenges in adopting autonomous drilling technologies due to, for instance, the strong perception that autonomy will result in job losses (Brown, 2014) and the view that the gains in efficiency from automated mining technologies will reduce the amount that mines contribute to government revenue in low- and middle-income host countries thus impacting local mining communities (Lovells, 2018).

According to Abbaspour et al. (2018), the mining activity is represented by four primary operations: drilling, blasting, loading, and hauling. They further highlight that in the context of open-cast mining, drilling, and blasting form the fundamental initial steps and have significant influence on the subsequent processes. These can also result in poor image due to potential environmental impacts (Bhandari & Bhandari, 2020). Autonomous drilling means independence from human presence and decisions about tasks related to the drilling process (Alves & Ortiz, 2023). Such capability seeks the optimization of the entire production sequence, and with current research, such is no longer a futuristic idea but a reality. Bhandari & Bhandari (2020) highlight that the technologies for optimizing drilling and blasting have largely been non-integrated and non-real time which presents a gap in the sustainability of these operations. That is, current methods particularly for planning and quality assurance/quality control (QA/QC) of these mining operations are paper-intensive and thus time-intensive while providing unreliable and non-auditable results (Klaric & Bodley, 2023). Mining, by its very nature, is subject to a high degree of volatility.

Without the proper coordination and integration of its various activities, coupled with a feedback mechanism through real-time reporting, managing, and mitigating this variability can pose a significant challenge. This is supported by Lazarenko et al. (2021), who suggest that while the benefits of automation are clear, the path to achieving them is yet to be fully comprehended. Therefore, the site-specific problem to be addressed is the lack of integration and effective use of the autonomous drilling system, which is aimed at enhancing operational efficiency, improve safety and promote sustainability in the mining sector. Hence, this research aims to bridge the gap by developing a comprehensive framework to facilitate the adoption and implementation of autonomous drilling in open cast mining operations, allowing the mining industry to fully leverage the transformative potential of autonomous technology.

1.4 Research Objectives

This section outlines the specific objectives that direct this research project.

The objectives include:

1) To evaluate the existing digital technologies used by mining companies.
2) Identify and examine operational factors affecting the drilling process and implementation of autonomous drilling systems.
3) Identify and analyse the key barriers to digitalisation and automation of drilling operations in mining operations.
4) Develop a framework providing strategic guidelines to mining companies for seamless adoption and implementation of autonomous drilling systems in open-cast mining operations.

1.5 Theoretical Frameworks

The adoption and integration of digital and autonomous technologies in open-cast mining are not purely technical exercises but require a structured and strategic approach that addresses both operational and non-operational barriers. To ground this study, an integrated theoretical perspective is adopted, drawing on the Technology-Organisation-Environment (TOE) Framework and the Diffusion of Innovation (DOI) Theory. As proposed by Dayo-Olupona (2020), mining companies must view technology as a value chain enabler and adopt a strategic technology roadmap to facilitate adoption and integration. The TOE framework, developed to explore organisational factors that influence technology implementation (Lumadi & Nyasha, 2024), identifies three contextual dimensions: the technological (existing and potential technologies), the organisational (resources, size, structure, and culture), and the environmental (industry conditions, market forces, and regulations) (Oliveira & Martins, 2010). These dimensions are critical for assessing readiness and ensuring compatibility and integration of technologies like autonomous drilling systems.

The Diffusion of Innovation (DOI) theory, as discussed by Lumadi and Nyasha (2024), explains how innovations spread across individuals and organisations through five stages: knowledge, persuasion, decision, implementation, and confirmation. This model emphasises how awareness, perceived benefits, stakeholder buy-in, and ongoing reinforcement shape the successful uptake of new technologies. In mining, these stages offer a pathway for understanding how operators, engineers, and decision-makers form attitudes and make decisions about adopting autonomous digital systems. Barriers such as lack of integration with existing systems, highlighted by Felipe Sanchez (2019) can derail adoption if not properly anticipated and addressed during these phases.

The integration of these two frameworks (TOE and DOI) offers a robust foundation for understanding both the contextual readiness and the behavioural processes underpinning the adoption of digital technologies in mining. While the TOE framework ensures a structured assessment of the technological infrastructure, organizational capacity, and external environment, the DOI theory allows for a nuanced understanding of stakeholder perceptions, attitudes, and behaviours throughout the adoption lifecycle. While the TOE framework ensures a structured assessment of the technological infrastructure, organizational capacity, and external environment, the DOI theory allows for a nuanced understanding of stakeholder perceptions, attitudes, and behaviours throughout the adoption lifecycle. As Dayo-Olupona (2020) highlights, successful technology integration in mining is not merely technical but strategic, requiring alignment across systems, people, and processes. This combined approach is particularly relevant given the common challenge in the mining industry of deploying technologies, such as autonomous drilling, in isolation, without adequate integration into existing systems

(Felipe Sanchez, 2019). By adopting an integrated TOE-DOI framework, the study aims to provide actionable insights that support technology adoption, strategic alignment, and continuous improvement of digital drilling systems in open-cast mining operations.

1.6 Delimitations of the study

The delimitations of the research study are:

i. The study is limited to the South African surface mining industry.
ii. The participants of the study are confined to a particular surface mining operation **(referred to as Site X)** and includes autonomous drilling system service providers who are employed within this specific operation.

1.7 Definition of terms

Digital mining: Also known as *Mine of the future*, "digital mining represents efficient mines that are smart and operated by highly skilled workers. The goal of "Mine of the future" is to develop an intelligent (smart) mining concept, so the industry can do more with less cost by taking responsibility for what mines do have control over –operational efficiency." ("*MINES OF THE FUTURE*," 2019)

Jelena and Kostić (2023), describe digital mining as smart mining, a concept that involves the application of advanced technologies, especially AI, to augment different facets of mining operations. The primary objectives include improving efficiency, cost reduction, safety improvement, and optimization of resource extraction processes. In essence, digital mining leverages AI and associated technologies to transform conventional mining practices, making them more efficient, economical, and safer.

1.8 Assumptions

The following assumptions are considered during the course of the research:

i. The study assumes that the participants are specifically involved in open-cast mining drilling processes and thus presumed to possess the experience and knowledge of autonomous drilling systems.

1.9 Chapter Outline

Chapter 1 introduces the study, highlighting the importance of optimizing open-cast mining drilling operations using digital technologies. It sets the context for the research on the adoption and integration of autonomous drilling systems (ADS).

Chapter 2 reviews relevant literature, exploring the diffusion of innovation theory and technology-organization-environment framework. It addresses barriers to technology adoption and analyses past research on technology uptake in the mining sector. Chapter 3 elaborates on the research methodology, justifying the application of the interpretivism paradigm and a qualitative, inductive approach with purposive sampling and semi-structured interviews to gather insights from industry and drilling phenomenon experts. This is followed by a discussion on data analysis through content analysis, quality assurance to measure data and analysis quality and ethical considerations to highlight key ethical considerations when conducting research.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Automation of critical activities in mining has the potential to improve safety while driving productivity and cost reduction. Whitfield (2022) states that automation in mining, including autonomous drilling systems (ADS) and autonomous haulage systems (AHS), has seen significant advancements and adoption in countries like Australia, the United States of America, Canada, China, and Chile. But its vision is yet to be fulfilled due to the automation of siloed sub-systems (*Drilling Automation: A System View*, 2023).

The adoption of drilling technology is crucial not only in the mining industry but also in the oil and gas sectors, directly impacting operational efficiency, safety, and overall productivity (Whitfield, 2022). Automation in drilling has emerged as a key focus area, promising to enhance performance and safety while addressing economic challenges. This literature review examines the progress and challenges associated with the deployment of autonomous drilling systems, drawing on recent developments and innovations in autonomous drilling technologies, autonomous drilling implementation case studies or examples, and insights on future trends.

The South African mining sector faces similar challenges to those encountered globally, including the need for improved safety measures and operational efficiencies (Sidler, 2014). As South Africa seeks to modernize its mining sector, understanding the potential and limitations of autonomous drilling systems is central to strategic technological adoption and implementation. Thus, the objectives of this literature review are fourfold: to evaluate the existing drilling technologies used by mining companies, to identify and examine operational factors affecting the drilling process and the implementation of autonomous drilling systems, to identify and analyse the key barriers to digitalisation and automation of drilling operations in mining operations and to develop a framework providing strategic guidelines for the adoption and implementation of autonomous drilling systems in open-cast mining operations. With focus on these objectives, the review methodically scrutinizes the advancements in and application of digital technologies in the mining sector, with special emphasis on ADS. The study assesses the development and transformation of digital technologies in mining, as well as the current status of autonomous drilling in the sector. Furthermore, it uncovers the potential barriers and challenges to adoption by evaluating important factors that influence the drilling process and understanding the perceptions of the mining industry towards autonomous drilling technologies. With these insights, the review intends to provide an up-to-date picture of autonomous drilling in the mining sector and assist in aligning ADS adoption with the organization's position and strategic goals.

2.2 Key digital technologies in the mining industry

The history of mining is a testament to technological evolution. Progressing from manual labour and use of basic tools in ancient times to the sophisticated digital operations of the 21st century (Kinematics, 2023). Globally, mining transitioned from basic tools to mechanization during the Industrial Revolution, significantly enhancing production with steam engines, drills, and explosives (Cartwright & Kregczy, 2024; Industrial Revolution | Definition, History, Dates, Summary, & Facts, 2024).

Casey (2024) and Nex and Kinnaird (2018) state that in South Africa, mining has been central to economic development, with a history spanning from indigenous gold and copper mining to large-scale operations following the 19th-century diamond and gold discoveries. Nex and Kinnaird (2018) continues to add that the post-apartheid era saw increased international investment and technological advancement, which may explain to an extent, why today, the South African mining industry is embracing digital transformation. While both global and South African mining sectors have benefited from mechanization and automation, the digitalisation phase presents unique challenges, including inadequate infrastructure, substantial investment needs, and workforce training requirements (Lumadi & Nyasha, 2024).

The ongoing technological advancements in mining are an indication to its significant influence on the industry's future, both globally and within the specific context of South Africa (Goodman & Rajagopaul, 2019). This part of the review evaluates the current technologies employed by mining companies operating in South Africa, particularly in their drilling activities.

Digital technologies and automation have a transformative impact on the mining industry operations, safety, and environmental management (Wozniakowski-Zehenter, 2024). The integration of digital technologies, often referred to as Industry 4.0, is revolutionizing mining operations and this is particularly relevant in the South African context because of how South Africa's economic fabric is significantly tied to mining activities with a Gross Domestic Product (GDP) contribution of around 11.18 billion US dollars in 2023 (Mining Sector's Value Added to GDP in South Africa 2016-2023, 2024; PT Pamapersada Nusantara, 2023).

The transition from conventional mining practices to digital operations is a fundamental aspect of digital transformation in mining. The transformation is primarily driven by the advancements in automation, the internet of things (IoT), advanced data analytics, machine learning, and artificial intelligence (AI), as emphasized by PT Pamapersada Nusantara (2023) and Wozniakowski-Zehenter (2024). For example, the Internet of Things (IoT) facilitates the remote monitoring of environmental conditions and equipment, thereby enabling an immediate response to any identified anomalies (Revolutionizing Remote Monitoring: The Internet of Things (IoT) in Action, 2023). This not only improves operational efficiencies but also, and most importantly, supports the zero-harm initiative in mining by enhancing safety. This is especially relevant to South African mines, which are among the most hazardous and deep operations in the world. In the context of surface mining, the utilization of automated equipment, such as drills and dump trucks, can significantly reduce human exposure to the changing environmental and ground conditions, thereby improving productivity and safety.

PT Pamapersada Nusantara (2023), lists the key digital technology types commonly used in the mining industry can be listed as follows:

1. Internet of Things (IoT): The mining industry has experienced a substantial increase in the prevalence of Internet of Things (IoT) devices and sensors. This may be attributed to the fact that IoT devices and sensors collect valuable data from a diverse range of mining equipment and processes (*IoT in Mining: Exploring Use Cases and Opportunities for Transformation*, 2021). Even though IoT devices can offer real-time information about the safety of workers, the status of equipment, and the current environmental conditions, mining companies encounter challenges

such as stable connectivity. This is particularly true in rural or isolated towns, where wireless networks are subject to consistent fluctuations.

2. Autonomous Equipment and Vehicles: Haul trucks, drilling rigs, and loaders are examples of autonomous equipment that are employed in both surface and underground mining environments. Advanced AI systems or remote control are employed to operate this equipment (Admin, 2023).
3. Advanced Data Analytics: Mining companies utilize data analytics tools and algorithms, such as Tableau, to analyze large datasets generated by mining operations to optimize processes and inform decision-making (Gregorio et al., 2020). Sontakke (2024) underscores that the mining industry can make data-driven decisions in areas such as resource management, environmental sustainability, supply chain management, and risk management by leveraging big data.
4. Artificial Intelligence (AI) and Machine Learning (ML): According to Admin (2023) and PT Pamapersada Nusantara (2023), predictive maintenance, ore grade optimization, and safety monitoring are all accomplished using AI and machine learning algorithms. They can identify patterns and anomalies in the data to make well-informed decisions.
5. Remote Monitoring and Control: In the mining industry, safety is the primary concern. Consequently, miners concentrate on minimizing the need for on-site personnel by remotely monitoring and controlling equipment and processes. This is especially beneficial in mining operations that are in hazardous areas.
6. Digital Twin Technology: Digital twins produce virtual replicas of physical mining assets and processes. They are utilized to optimize, monitor, and simulate operations, thereby enabling mining companies to make informed decisions and reduce downtime.
7. Drones and unmanned aerial vehicles (UAVs) are utilized to survey, map, and monitor mining sites. They have the capacity to rapidly collect information regarding terrain, stockpiles, and infrastructure (PT Pamapersada Nusantara, 2023).

8. 3D printing technology is an additive technology that does not necessitate a mould to produce or generate prototypes and customized components (*3D Printing: What Is It & How Does It Work? | Protolabs Network*, 2024). Mining can utilize this technology to manage their supply chain for equipment spare parts, which are typically solely dependent on original equipment manufacturers (OEMs), despite its prominence in the engineering and healthcare sectors.
9. The transparency and traceability of the mining industry's supply chain can be enhanced by blockchain technology. Blockchain technology can enable the monitoring of the life cycle record of minerals during the import and export process, thereby ensuring responsible sourcing (Fasken, 2022).
10. The mining industry is being revolutionized by digital technologies such as virtual reality (VR) and augmented reality (AR), as noted by the Mining Journalist (2024). VR and AR have a wide range of applications, including training, simulation, high-risk work planning, and maintenance. They improve the efficiency of training and troubleshooting by allowing workers to visualize complex equipment, processes, and the surrounding environment (Fade, 2023).
11. Environmental Monitoring and Management: Digital technologies are employed to monitor environmental impact and regulatory compliance. This includes the monitoring of emissions and the quality of air and water (Crawford & Hill, 2021).
12. Cybersecurity: Considering the increasing trend of digitalization, cybersecurity is imperative to protect sensitive data and prevent cyberattacks on mining operations (Huq, 2016). Mining is complex because of the interconnectedness of the majority of its processes and equipment, necessitating customized controls to mitigate cybersecurity risks.
13. Geographic Information Systems (GIS): GIS technology is implemented to enhance the layout of mining sites, conduct geological mapping, and conduct spatial analysis (PT Pamapersada Nusantara, 2023).
14. Robotics: According to Poojaallawadhi (2023), robotics mining is the process of extracting minerals and/or resources from mining operations using autonomous or remote-controlled robots. This is especially beneficial in hazardous or harsh

environments, where robotic systems can be implemented to perform tasks such as rock breaking, and material handling, to name a few.

15. Energy Management: By implementing smart grids and energy management systems, mining companies can optimize energy consumption and decrease operational costs (Owen, 2024; PT Pamapersada Nusantara, 2023).

2.2.1 Digital drilling technologies

2.2.1.1 Open-cast mining drilling process

Eedev (2019) explains that the drilling process in open-cast mining is a critical unit operation in the removal of large quantities of overburden to expose ore deposits in the type of mining. This is further supported by Smith-Wong (2024), who emphasizes that the drilling process prepares the site for blasting and the subsequent removal of material.

The drilling process outlines by Eedev (2019) is as follows:

1) The first step prior to drilling the hole is to survey the site. That is, analyze the nature of the ground and mineral to be drilled. The data gathered at this step enables for decision making around the drill design and decision-making around hole characteristics and drill type to be used to ensure effectiveness of the process.
2) Step two (2) involves planning, which is the design of the drilling pattern, finalizing the design parameters and operational parameters based on the geological conditions Kumar et al. (2020).
3) Step 3 involves performing a staking process- marking of the drill hole locations on the bench/block to ensure that the drilling operation adheres to the planned design.
4) In this step, the actual drilling of blastholes commences, in line with the approved drilling design. At this point, all safety controls need to be in place to ensure that the drill operates within the set limits. For instance, **site X** uses large cones to demarcate drill area which serve as boundary limit points preventing drills from being operated beyond those points.

2.2.1.2 Autonomous drilling systems

Autonomy in drilling equipment is now standard – ranging from remote control, tele remote and semi-autonomous to autonomous (Vella, 2024). In response to the pressure to improve profitability and satisfy the ever-increasing demands for safety and environmental friendliness, the adoption and deployment of autonomous drills in open-pit mines has seen considerable growth (Atlas Copco, 2016; Vella, 2024). Several Original Equipment Manufacturers (OEMs), including but not limited to Sandvik, Flanders and Epiroc offer advanced drilling technologies. These technologies include:

- SmartROC: Autonomous surface mining pit vipers equipped with Rig Control System (RCS) algorithms for drilling process optimization.
- Auto Rod Handling System (Auto RHS): This system allows for the automatic addition of rods to reach the desired depths.
- Hole Navigation System (HNS): This system guides hole positioning as per drill plan (*Automation Tools and Technology That Optimize Your Machine's Performance*, 2024; Turner, 2017).

Other notable drilling technologies include:

- Sandvik's AutoMine concept: A fully autonomous twin-boom drill rig that uses an AI guided drill bit changer to identify when bits are worn and changes them automatically (French, 2022). Moreover, this system is capable of planning and executing an entire drilling cycle autonomously (NextGenAutomation, 2023).

Although most autonomous drilling systems are equipped with camera systems for remote control and sensors and software for data collection such as Rock Pulse AI, these systems are not integrated with the existing mining infrastructure such as the fleet management system, which creates a gap in wholistic/interconnected data analytics thus delaying the performance optimization process.

2.2.2 Autonomous drilling systems: Use cases and impacts

Rio Tinto, Pilbara (Western Australia)

Rio Tinto initiated its first implementation of autonomous drilling systems (ADS) in 2008, focusing on West Angelas mine; by 2018, the company had significantly expanded the implementation of ADS to its other operations (Turner, 2018). The basis of implementation was primarily to improve safety at its operations by minimizing human exposure to hazardous work conditions.

Through the ADS technology, operators were able to control multiple drill rigs remotely from an operations control centre located over 1500 kilometres away (*Rio Tinto to Almost Double Its Autonomous Drilling Fleet in a Drive to Further Improve Safety and Productivity*, 2018).

Apart from the minimal human intervention, Turner, 2018 and *Pioneering Automation and Robotics in Mining, 2024* emphasize the subsequent benefits of ADS implementation as follows:

- Enhance safety: Operators are removed from line of fire, thus reducing the risk associated with working with and around heavy machinery.
- Improved productivity: It can operate longer hours without fatigue thus enabling the mines to improve their productivity in drilling.
- Autonomous drilling increases execution accuracy which translates to enhanced process efficiencies.

Anglo American, Kumba Iron Ore (South Africa)

As part of Anglo American's strategy of creating a smart, safe, and clean future in the mining industry, technologies like ADS became paramount at enabling the mine to solve some of its biggest challenges and transform their way of work (Anglo-American, 2022). In 2021, Anglo American initiated the autonomous drilling project at its Kumba Iron Ore operations. Numerous challenges around pit readiness, IT infrastructure and systems readiness and operator training resulted in the first ore production occurring in year 2023. The Kumba Iron Ore operations are yet to reach the point of complete autonomy in drilling; however, their implementation has yielded benefits: The challenges faced by drill rig operators, including noise, vibrations, and dust, were discussed by an operator who had been employed by the company for 11 years (Anglo-American, 2022). However, with ADS, all operations are managed remotely, thereby removing operators from potentially hazardous work environments. Additionally, ADS allows for continuous operations, which in turn enhances resource utilization and productivity. The Kumba Iron Ore operations have experienced an average 10% improvement in drill optimization (Gleeson, 2022).

Having evaluated the digital technology landscape of the mining industry and examining a few use cases, it is evident that there is ongoing transformative change in mining practices particularly in drilling activities- from traditional to smart/digital mining. Despite the notable difficulties around infrastructural requirements, skills development needs and associated investment costs, mining companies are not laggards (*Digital Transformation in Mines - SMART Mining Security Solutions 2024 - NEC XON - Technews Publishing - SMART Security Solutions*, 2024). It does appear that the deployment of autonomous drills in South Africa has been more gradual than in Australian and Swedish mining operations. But, since the second quarter of 2021, there has been a notably growing interest in Southern Africa with Anglo American implementing autonomous drilling systems in three (3) of its South African operations: the Sishen and Kolomela mines (Iron Ore) and Mogalakwena mine (Platinum Group Metals) (Anglo-American, 2022). The dawn of the digital age promises a bright future for the mining industry at large and especially for South Africa whose mining sector is a significant factor in the country's economic growth.

2.3 Examination of Operational Factors Affecting the Drilling Process and Implementation of Autonomous Drilling Systems

2.3.1 Blasthole drilling

Blast hole drilling is conducted with the help of large drilling machines, which are used to create holes for blasting as stated by Rout et al., (2007). This procedure facilitates the removal of large quantities of ground material, thereby providing more accessible access to the underlying minerals. Epiroc, (2022) mentions that while there are alternative methods for rock displacement for excavation, such as gas pressure blasting pyrotechnics, the technique that involves drilling and inserting explosive charges into the drilled holes remains the most prevalent in surface mining environments.

2.3.2 Factors impacting the drilling process

There are several drilling factors that affect the output of a drilling process. These factors can be generally classified into two main groups: controllable and uncontrollable factors.

In mining operations, controllable factors are those elements that engineers can adjust to enhance drilling efficiency and safety (Munagala et al., 2024). Conversely, uncontrollable factors, which include external variables and fixed design features, cannot be directly altered but must be factored into both the planning and operational stages. The ability to recognize and adapt to the factors is key in creating flexible drill plans, thereby optimizing the process, and ensuring compliance with efficiency and safety norms of open-cast mining.

Gadikor (2018); Munagala et al. (2024); and Taviti Naidu et al. (2020) identify these factors as follows:

Table 1: Factors impacting the drilling process
source: Author constructed, (2024)

Controllable Factors		Uncontrollable Factors	
Design Parameters	**Operational Parameters**	**Geological/Weather Conditions**	**Drilling Performance**
Blasthole characteristics	Rotations per minute	Rock density & strength	Rate of penetration
Bit and rod design	Weight on bit	Ground/geological conditions	Torque
Burden and spacing	Rate of flow of drilling fluid	Weather conditions	Injection pressure
			Instantaneous drilling

Uncontrollable factors

- Rock density and strength

Rock density and strength are inherent rock properties which have a significant impact on the drilling process. For instance, the harder and denser a rock is, the more energy it will require and time to drill through.

- Ground/geological conditions

Variations in ground stability, moisture content and the presence of geological formations such as faults, and fractures pose safety concerns in drilling and compromise the stability of the blasthole and the efficiency of drilling activities.

- Weather conditions

Weather conditions such as wind and rain, to name a few, introduce a level of unpredictability and can thus affect the performance of drilling equipment and the safety of drilling operations. For instance, in case of heavy rainfall, area visibility for the drill rig operator is impaired and the rain may cause ground instability which in turn affects drilling accuracy.

- Rate of penetration

This indicates the speed at which the drill bit penetrates the rock. This is mostly influenced rock mass properties. A high rate of penetration equates to a fast rate of drilling but may affect drill bit rate of wear.

- Torque

Torque is the rotational force required to turn the drill bit to break the rock mass. Similar to rate of penetration, torque depends on the ground heterogeneity, therefore, a higher torque increases speed of rock mass penetration.

- Injection pressure

Injection pressure is that of the drilling fluid injected into the blast hole. This pressure facilitates the removal of cuttings from the hole more efficiently but is dependent on ground conditions encountered.

- Instantaneous drilling time

Inversely proportional to rate of penetration but influenced by ground conditions, instantaneous drilling time is the time taken to drill a certain length of a blasthole.

Controllable factors

- Burden and spacing

These parameters dictate the placement and pattern of drill holes. Burden speaks to the distance from the blasthole to the nearest free face, while spacing is the distance between blastholes. These parameters influence the effectiveness of a blast in that they can ensure rock breakage and minimize ground vibrations.

- Blasthole characteristics

This encompasses the diameter, depth, and orientation of the blastholes. These characteristics can be adjusted in line with the ground conditions and desired blast outcomes as they affect the efficiency of rock breakage and the stability of the remaining rock mass.

- Rotations per minute (RPM)

RPM is the speed at which the drill bit rotates, and it affects the overall drilling speed. Though a higher RPM can increase penetration rate of the bit, it can also impact the life of the drill bit.

- Weight on bit (WOB)

Weight on bit is a factor thar influences the force exerted on the drill bit, impaction tool wear and speed of penetration. When adequately managed, the WOB can help ensure efficient rock breakage without causing excessive wear on the bit.

- Bit and rod design

The design and material of the drill bit and rod can affect the life of the drill bit, blasthole stability and speed of penetration thus impacting the performance of drilling and the durability of the drill rig parts.

- Rate of flow of drilling fluid

This is the rate of flow of water used in the drilling process into the drilled hole. The water is essential for cooling the drill bit, removing cuttings from the drilled hole, and maintaining blasthole stability.

Supporting the controllable and uncontrollable factors are service factors. These pertain to the support and maintenance aspects that impact the drilling process. These factors include:

- Drilling equipment maintenance

To ensure continuous operation, it is crucial to conduct preventative maintenance routines and ensure timely repairs upon breakdown of drilling equipment.

- Availability of spare parts

Managing the supply chain of critical spare parts of drilling equipment reduces downtime from unplanned breakdowns and possible overruns on scheduled equipment overhaul services, thus keeping the process efficient.

- Training of operators

Training operators improves the way in which they handle the equipment and enables them to adapt to changing conditions.

- Safety and regulatory compliance

Standard operating procedures are used to define safety and regulatory protocols, and to train operators and other stakeholders to minimize any potential risks. The safety factor encompasses personnel, machinery, and the environment. In autonomous drilling, the three facets of safety are addressed through the use of interlock systems, which are designed to prevent unexpected but anticipated unsafe events during drilling operations. An interlock system comprises sensors (which are input devices that detect surrounding activities), and control and logic components (which use algorithms to trigger responses to the activities detected by the sensors).

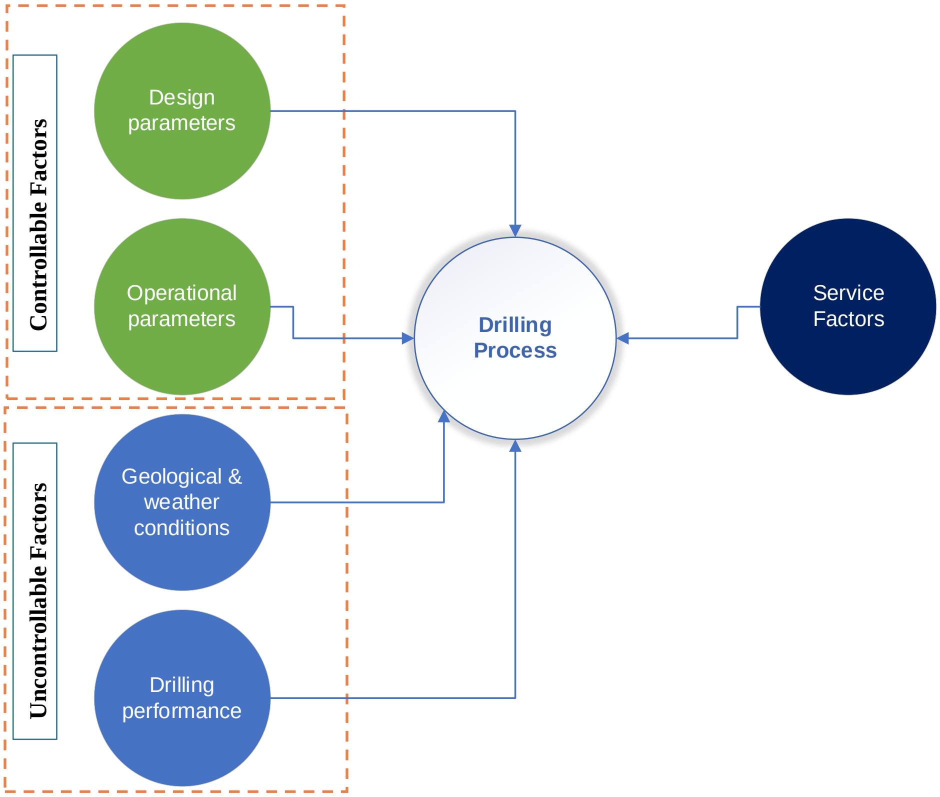

Figure 1: Factors affecting the drilling process
source: Author constructed, (2024)

2.3.3 Exploring key factors in autonomous drilling: Impact of loading and block cleaning

Examining the taxonomy of factors involved in the drilling process, as depicted in Figure 1, and their connection to the adoption and implementation of autonomous drilling, leads the author to classify the most important factors into two primary categories specific to **site X**: (i) Preceding mining activities and (ii) Safety. The classification hinges on the premise that the operational factors, both controllable and uncontrollable maintain their relevance regardless of whether the drilling process is conventional or autonomous. However, there exists service/support factors that, if not properly addressed and consistently managed, can inhibit the applicability and feasibility of ADS in surface mining operations.

The first category, *preceding mining activities*, focuses on maximizing efficiency gains from accurate execution of activities that precede drilling. Surface mining encompasses the following sequence of unit operations: Clearing the land of vegetation, topsoil removal, drilling, blasting, loading, hauling, dumping, crushing, and screening (Munagala et al., 2024 and Evans & Ramani, 2024). Considering that with traditional drilling activities, an operator can navigate through any conditions (whether favourable or not), the key activities in open-cast mining that enable efficiency gains and increased production are block preparation and loading.

The second category, *safety,* concentrates on the unfavourable site conditions that pose a risk to human safety. These conditions include noise, vibrations, high voltage live power and dust exposure (Anglo-American, 2022).

Vella, (2024), emphasizes that operational consistency stands as a major key performance indicator in autonomous drilling. This encompasses not just the technical facets of autonomous drilling like hole navigation, managing transition time and attaining accurate hole depth, but also underscores the importance of spatially orchestrating the activity for successful outcomes.

Aguayo et al. (2021) describe loading in open-cast mining as the process of transferring mined materials, such as ore or overburden, from the mining site to dumping zones and processing facilities using dump trucks. Within the broader scope of mining operations, loading is an important unit operation as it facilitates the movement of extracted material away from the mining site. Similarly, with block preparation, also known as block cleaning, is a process that takes place after a blast, where fragmented material is cleared to prepare the area for drilling activities. These unit processes are closely connected, as efficient loading practices ensure about 90% block cleaning compliance, thereby, minimizing operational delays due to excess cleaning requirements and poor cleaning equipment availability on block cleaning activities and facilitating continuous operations.

However, **Site X**, encounters difficulties due to suboptimal loading practices and low availability of cleaning equipment such as dozers, resulting in uneven floors and irregular blocks. These conditions are not conducive for the application of ADS, which necessitates near-perfect floor conditions in terms of elevation.

A little over a year ago, **site X** experienced a fatality within its drilling operations, hence drilling is recognized as one of the riskiest operations in mining. Various levels of automation allow drill rigs to operate largely autonomously, thereby eliminating or significantly reducing operators' exposure to hazardous conditions such as dust, vibrations, and noise. However, the persistent lack of integration between upstream and downstream mining activities perpetuates substandard practices in loading and block cleaning. This not only continues to expose drill rig operators to hazardous working environments but also hinders the potential sustainability of using ADS in open-case mining environments due to underutilization and restrictive spatial conditions.

In the transition from traditional to autonomous drilling, controllable and uncontrollable factors, such as RPM, WOB and weather conditions, to name a few, consistently impact drilling operations. Emphasizing safety, efficiency, and sustainability, these factors directly influence operational consistency and highlight the need to continuously assess process data and conditions to mitigate and/or significantly reduce risks that operators may be exposed to and the intrinsic instability inherent in mining operations.

However, the site-specific challenges, particularly those that relate to service/support factors, such as suboptimal loading practices and substandard block preparation, highlight the need for integration between upstream and downstream mining activities. These activities significantly influence the quality of drilling operations, which in turn, impact the quality of blasting operations. The ripple effect can lead to decreased efficiencies and increased costs. Therefore, prioritizing the improvement of bench drilling efficiency and performance in open-cast mines is a priority, as the drilling operation influences the blasted quantity, particle size distribution of fragmented material, fill factor of shovel and truck, and input size of the crusher (Uhuru & Kumral, 2019).

2.4 Non-operational barriers to digitizing and automating drilling operations in mining

According to Olajiga et al. (2024), the. mining industry has been transformed by the advent of smart drilling technologies. These technologies have improved safety, efficiency, and promoted sustainability. Yet, despite these advantages, the digitalisation and automation of drilling operations face substantial challenges. Given the complex nature of mining and it associated processes, Khogali and Mekid (2023), Ramdoo and others (2021), and Sager and Soy (2021) identify several key potential barriers to automation. These barriers are summarised in Figure 2.

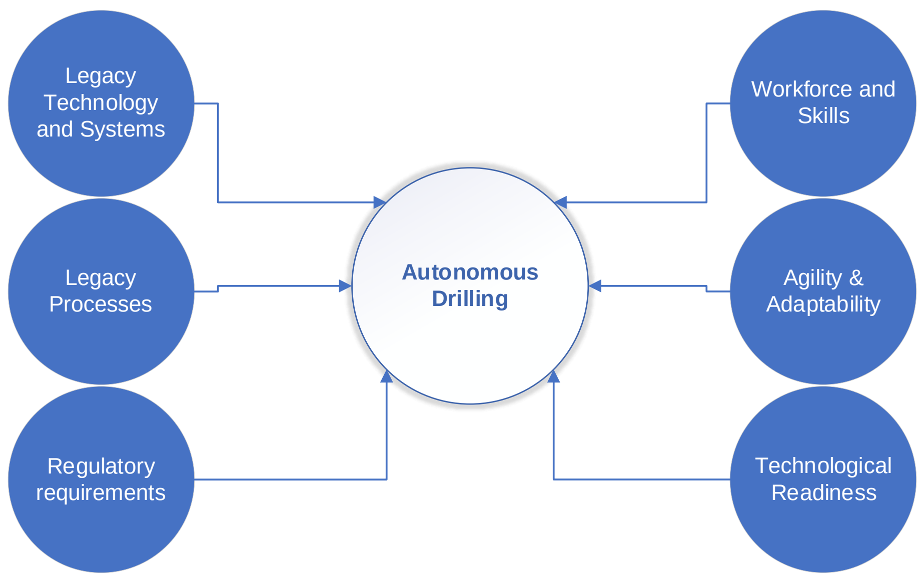

Figure 2: Barriers to digitalisation and automation in mining
source: Author constructed, (2024)

1. Legacy Technology and Systems

Legacy technology and systems refers to older technology embedded within the organization's operations. The challenge with these technologies when it comes to digitalisation and automation is that they may lack compatibility with modern digital tools due upgrade failures, thus creating technical (operational inefficiency and disruption) and integration (data siloes) difficulties.

2. Legacy Processes

The design of existing processes and workflows is primarily done around the *legacy technologies and systems.* Often, the transition from traditional to digital processes calls for a potential overhaul of the established practices and/or rethinking or reengineering them. Failure to adapt to these changes increases risk of error in the newly implemented workflows, thus limiting the effectiveness of digitalisation and automation.

3. Regulatory Requirements

The mining industry as a whole is heavily regulated and considering that drilling is classified as one of the riskiest operations, the level of scrutiny with implementing digital technologies is high. Concerns around upholding safety protocols, protecting the environment and overall legal compliance can create a resistance from the affected operators and if not addressed for full compliance, lead to unwanted safety incidents, operational stoppages through Section 54 of the Mine Health and Safety Act, as a result of dangerous conditions (UCT, 2018).

4. Workforce and Skills

It is inevitable that with digitalisation and automation the workforce will reduce considerably. The barrier of workforce and skills goes beyond jobs losses and involves the redefinition and disruption of tasks. Changing the nature of a task such as drilling, calls for a change in the associated skills and competencies to perform the task. Ramdoo et al. (2021) states that the advancement of digital technologies in mining have uncovered a challenge of skills gap and mismatch. The author adds that the effect of a skills shortage and mismatch could significantly affect the mine's ability to recruit within the areas in which they operate, thus preventing them from benefiting from new technologically intensive job prospects.

From the Table 2, there is a clear indication that other occupational categories will cease to exist in the mining context thus deeming them redundant or requiring restructure of most tasks- the same holds for autonomous drilling. Although, training offers opportunity for upskilling and potential career growth, this change affects overall operator morale. That is, mining operations are often in rural settings where average education is low, thus those operators face redundancy due to the lack of expertise.

Table 2: Labor market dynamics in mining
source: (Ramdoo et al. 2021)

FUTURE (OR NEW) TECHNOLOGIES	CHANGES OCCURRING	REASONS FOR CHANGE	EXAMPLES OF OCCUPATIONS AFFECTED
Autonomous Vehicles AI and ML	Task redundancy	Obsolescence	Vehicle conductors, engine drivers, mining extraction workers AI and ML specialists
Blockchains			Data entry clerks, material recording and stock-keeping clerks
Unmanned Vehicles (Drones)			Prospectors, data analysts and scientists
Remote Sensing			Remote sensing scientists and technologists
Blockchains	Tasks restructured	Redesigned occupations	Accountants, procurement officers, financial analysts
Big Data			Management and organization analysts, Big Data specialists
Automation			Machine operators, remote control operators
Connected Wearables	Tasks augmented	Modernized occupations	Geologists, mining engineers, surveyors
Drones			Data analysts and scientists
Remote Sensing			Remote sensing scientists and technologists
Virtual Reality			Engineers, remote control operators, data analysts
Digitized Systems	Tasks outsourced / made flexible	Remote working	Vehicle conductors, machine operators, tele-operators
Software Automation			Report analysts, surveyors, machine operators, remote controllers
Virtual Reality	Capitalization effects	New tasks entering mining and organizational structures	App developers, software developers, Big Data analysts

5. Agility and Adaptability

The capacity of a mine to quickly adapt new technologies is a critical factor in the successful integration of digital technologies. The absence of such agility could result in a slow transition, an inability to fully exploit the advantages of automation, and ultimately, missed opportunities for growth. This principle is not only applicable to the adoption of new technologies, but also to the introduction of new processes. In these situations, a degree of adaptability is essential for the smooth implementation and integration of these processes into the mine's existing systems.

For instance, consider a mining company that needs to implement a new autonomous drilling system. If the company is agile and adaptable, it can efficiently train its employees on the new system, integrate the system with its existing data infrastructure, such as the fleet management system (FMS) and start using the system to drive efficiency, improve equipment utilization and ensure sustainable drilling practices through data-driven decisions. On the other hand, if the company is not agile or adaptable, it may struggle with these tasks, which could delay the benefits of the new system and potentially lead to discontinuation of the system.

6. Technological Readiness

The practicality and ease of deploying digital technologies and automated systems in the mining sector are influenced by the current status of the mine's technological infrastructure. This infrastructure encompasses elements such as the mine's tech stack and network capabilities, among others.

For example, if a mine has a robust technological infrastructure, including a high-speed network and modern servers, it may be easier to implement new digital technologies. These technologies could range from automated drilling systems to advanced data analytics software. However, if the mine's technological infrastructure is outdated or inadequate, it may face challenges in implementing these technologies, which could hinder its digital transformation efforts. Therefore, assessing and improving technological readiness is a crucial step in digitalisation and automation of mining processes.

2.4.1 Technology and Innovation Adoption Theory

The integration of digital and automated systems in open-cast mining presents unprecedented opportunity to enhance efficiency, productivity, and safety. However, the successful implementation of these technologies in not merely technical, but it requires a strategic approach that also addresses the various non-operational barriers. According to

Dayo-Olupona (2020), mining companies need to recognize technology as a process enabler and strategically prioritize technological integration across the mining value chain. The authors adds that there is a dire need for a coherent technology roadmap and strategy to help facilitate technology adoption and implementation within the mining industry. Therefore, to navigate these challenges and shortcomings, the author proposes the utilization of an integrated technology and innovation adoption theory, specifically the Technology-Organization-Environment (TOE) framework and the Diffusion of Innovation (DOI) theory. Lumadi and Nyasha (2024) describe TOE as a framework developed to identify aspects or features of an organization's context that influence the process by which it adopts and implements technological innovations. Oliveira & Martins, (2010) outlines the three features of the organization's context as follows: (i) Technology, which describes the existing technologies the organization uses and those that it could potentially adopt. (ii) Organization, which refers to the characteristics of the organization such as size, scope, resources, and structure, and other support/service factors such as organizational culture. (iii) Environment, a context referring to the external setting in which the organization functions, including its industry, competition, and government regulations.

The Diffusion of Innovation (DOI) theory developed by Everett Rogers in 1983 explains how, why and at what rate new technologies and innovations spread (Lumadi and Nyasha 2024). The authors add that the DOI process consists of five stages, namely knowledge, which speaks to awareness; persuasion, which speaks about the perceived characteristics of the innovation; decision, which is speaks to the acceptance/rejection of the innovation; implementation and confirmation, both of which address the use of the innovation and seeking for reinforcement for the decision and either continuing or discontinuing with the use of the innovation.

The lack of technology integration with existing company systems and tools was highlighted by (Felipe Sanchez, 2019) as commonplace in the mining industry. That is, the unprepared manner in which most mining companies approach technology adoption and implementation is a major stumbling block to leveraging fully the benefits of digitalisation and automation. This barrier is often overlooked. Hence, as seen at **site X**, the autonomous drilling system was deployed in isolation – without any integration to existing systems. Consequently, there was no way to evaluate its performance or the return on investment (ROE).

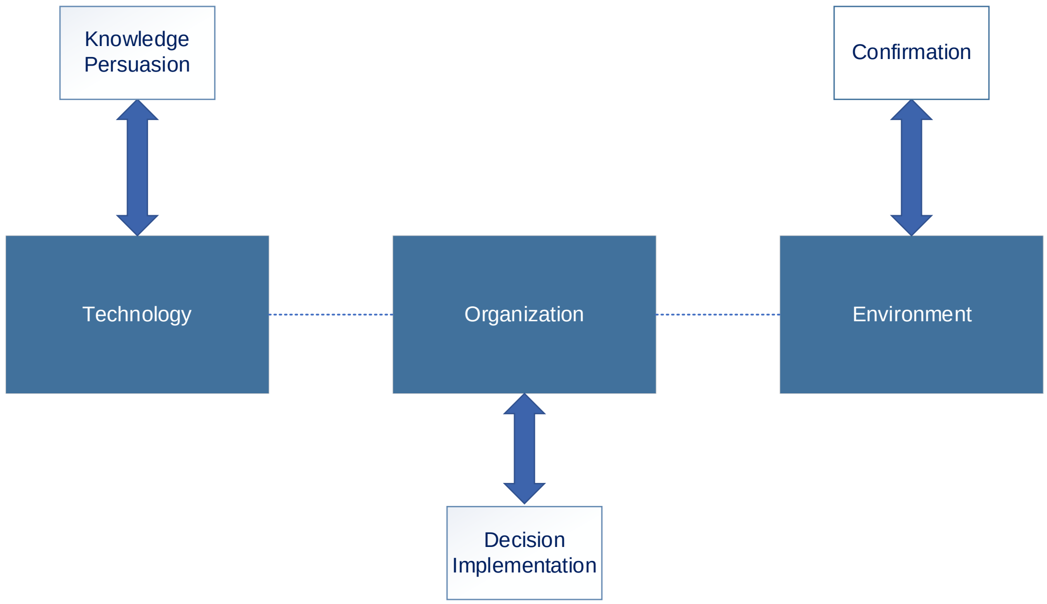

Figure 3: Integrated TOE & DOI Framework
source: Author constructed, (2024)

In the context of the TOE framework, assessing the current technological infrastructure is crucial for determining how autonomous drilling systems can be integrated with existing systems. Ensuring compatibility and seamless integration will minimize disruptions and enhance operational efficiency.

From the DOI perspective, the knowledge and persuasion stages are essential in building a foundation for technology adoption. Educating affected parties about the capabilities and benefits of autonomous drilling technology involves disseminating detailed information about how the technology works and the improvements it brings. Following this, the persuasion stage focuses on demonstrating the tangible advantages of the technology, such as increased efficiency and productivity, enhanced safety, and cost savings. Effective communication increases the likelihood of developing a positive attitude toward the adoption of the new technology.

Within the organizational context of the TOE framework, evaluating the organization's characteristics is vital because it helps in crafting a tailored approach that aligns with the organization's capabilities and needs. The decision stage of the DOI theory aligns with this by involving key parties in the decision-making process which ensures that the decision to adopt autonomous drilling technology is well-informed and has broad support within the organization.

The implementation stage, as highlighted by the DOI theory, involves executing the adoption plan through structured implementation plans, and phased rollouts.

The environmental context of the TOE framework emphasizes understanding the industry and market structure, which includes the competitive landscape and regulatory requirements that influence technology adoption (Oliveira & Martins, 2010). This enables the organization to navigate external pressures that drive the adoption of autonomous drilling systems effectively.

In the DOI theory, the confirmation stage involves continuously evaluating the performance and benefits of the technology post-implementation (Lumadi and Nyasha 2024). In the case of site X, one challenge is the quality and availability of data (K-Mine, 2023). Autonomous drilling systems rely on sizeable amounts of data to learn and make accurate decisions and this stage necessitates systems integration to enable for continuous monitoring and refining of the system.

Integrating the TOE and DOI offers the comprehensive strategy needed to address factors influencing the adoption of ADS across different stages and ultimately aid in smooth transitioning, ensuring system integration and establishing a feedback look to gather data and insights for continuous improvement and process adjustments. Both frameworks offer a holistic view. That is, DOI focuses on the organizational and individual attitudes and behaviours towards innovation thus not only providing insight into persuasion but also facilitating adoption of digital technology in mining; and TOE offers a broader perspective which ensures oversight of organizational preparedness and compatibility.

CHAPTER 3. RESEARCH METHODOLOGY

The research methodology outlines the approach that will be employed to address and/or meet the research objectives. This chapter offers an overview of the research techniques that will be utilized for this study.

3.1 Research Paradigm

According to Pretorius, (2024) and Arif, Habbe & Rasyid, (2023), there are four different research paradigms – positivism, realism, critical theory, and interpretivism. The authors states that a research paradigm explains what you believe reality is and how you think knowledge can be understood. Supporting this view or definition, Yong & Md Husin, (2021), describe a research paradigm as a set of assumptions that provide a conceptual framework or philosophical one for a world view, which enable researchers to construct organized studies around the world. A paradigm serves multiples purposes to the researcher such as, guiding the researcher as it indicates the important issues challenging any discipline; it allows the development of models and theories that enable for solving discipline issues; it establishes a criterion for research tools required and it provides the principles, procedures, and methods to be considered when similar issues reappear (Yong & Md Husin, 2021). These authors stress the importance of understanding research paradigms, as they guide scientific research and discoveries through their underlying assumptions and principles.

The adoption and implementation of digital technologies in any discipline, presents growth opportunities, competitiveness and other benefits and considerable amounts of challenges for organizations, its employees, and the communities in which they operate. This is particularly true for the mining sector. Besides the known benefits and spotlight challenges such as skills transformation, regulatory requirements, and resistance; the integration of technologies such as ADS with the organization’s existing tech stack is often overlooked, yet it plays a critical role on sustainability of digital solutions. For this study, it is argued that to leverage the full benefits of autonomous drilling systems, merely adoption and implementation is not enough. To promote utilization of the system to its highest potential, it needs to be integrated with the existing systems instead of being operated in isolation. To understand this holistically, an Interpretivism Paradigm is employed. This paradigm emphasizes understanding the individual interpretations and subjective meanings that people assign to their experiences (Pretorius, 2024). Contextually for **site X**, this paradigm is ideal for examining the site-specific conditions and cultural practices influencing ADS. Through the understanding of the research participants' experiences, the study can is able to comprehend the challenges and opportunities associated with the adoption of ADS in open-cast mining and its integration with the mine's systems thereof.

3.2 Research Strategy

The decision on research method is made by looking at how the researcher uses theory, theoretical and conceptual frameworks (Yong and Md Husin, 2021). The study aims to develop an adoption and implementation framework of autonomous drilling in open-cast mining operations mostly through the exploration of human and technical aspects of integrating ADS. While Yong and Md Husin (2021), suggest that the interpretivism paradigm allows the adoption of two types of research methods that can be adopted – quantitative and qualitative research, this study will make use of a qualitative research strategy. Hennink et al., (2020) describe qualitative research as an approach that allows the researcher to examine people's experiences in detail by using a specific set of research methods such as in-depth interviews, focus groups, observations, content analysis, visual methods, and life histories or biographies. This is approach is further supported by Creswell (2009), who highlights that the process of qualitative research is largely inductive, enabling the researcher to generate meaning directly from the data collection in the field. Hence, the research follows an inductive approach. According to Gaokgorwe (2023), the inductive research approach as one that concentrates on theory application and creation, pursuit of dominant patterns using observations, explanations, and/or hypothesis. On an exploratory level, specific to this study, the data collected from interviews will allow for in-depth exploration into how mining section leaders and autonomous drilling systems service providers perceive and interact with the system. That one the study can capture a broader view of the operational and contextual factors that influence ADS.

The decision to employ qualitative research guided by the interpretivism paradigm and inductive research approach, aligns with the study's objectives as it facilitates an understanding of the complex and nuanced human and technical factors involved in the adoption and implementation of autonomous drilling systems in open-cast settings.

Table 3: Study consistency matrix

No.	Research Objectives	Theoretical Framework Link	Aligned Interview Questions
1	To evaluate the existing digital technologies used by mining companies	**TOE**	- What are the current drilling practices at your site? - What inefficiencies or challenges do you experience with current processes? - How are these inefficiencies currently addressed?
2	Identify and examine operational factors affecting the drilling process and implementation of autonomous drilling systems.	**DOI: Compatibility** **TOE: Technological Context**	- Are you aware of or have you used digital drilling solutions? - How do you believe these tools could optimize current processes? - What benefits or concerns do you associate with them?
3	Identify and analyse the key barriers to digitalisation and automation of drilling operations in mining operations.	**TOE: Technological, Organisational, Environmental Contexts** **DOI: Complexity, Trialability, Observability**	- What do you see as the main barriers to implementing autonomous drilling systems? - Are there infrastructure, system, or skills limitations? - What role does regulation or policy play?
4	Develop a framework providing strategic guidelines to mining companies for seamless adoption and implementation of autonomous drilling systems in open-cast mining operations.	**DOI: Innovation Decision Process** **TOE: Organisational Context**	All questions including: - How ready do you think your organisation is for digital change? - What level of support or resistance is present among different stakeholders? - How would adoption affect your daily role? - What would help ensure successful adoption of digital/autonomous drilling technologies? - What kind of support, training, or partnerships would be needed? - What external help is needed?

3.3 Methods for Data Collection

Research method is one of the major elements of in research studies. It involves forms of data collection, analysis and interpretation proposed by the researcher for their study (Creswell, 2009). This is supported by Gaokgorwe (2023), who highlights that data collection comprises gathering data on the manifestation of the study phenomenon in an organized and recognized manner that permits response of the study sample to research questions and results.

Hennink et al., (2020), states that in qualitative research, selecting appropriate data collection methods is crucial and provides some commonly used methods as shown in Table 4.

Table 4: Qualitative research data collection methods
source: (Hennink et al., 2020)

	In-depth interviews	**Focus group discussion**	**Observation**
Objective	To identify individual perceptions, beliefs, feelings, and experiences	To identify a range of opinions on a specific issue or seek community norms	To observe how people act and interact in certain social situations
Research instrument	Interview guide	Discussion guide	Observation guide
Advantages	Gain in-depth information	Group interaction provides range of issues and opinions	Unobtrusive
	Identify personal experiences	Discussion provides detail, justification, and clarification	A lot of contextual information
	Useful for sensitive issues	A lot of information collected quickly	Supports data from other sources
	Identify context of participants' lives	Identify key issues	Identify people's actual behaviour
		High emancipatory effect	Conduct in many situations
	No interaction or feedback from others	Less depth of information	Interpretation of observations may be subjective

Disadvantages	Individual perceptions only	Less suitable for personal experiences	Distinction between participation and observation is needed
	Multiple interviews needed to identify range of issues	Managing group dynamics	

Selecting a suitable method depends on the research study questions and objectives. Although combining multiple methods has the potential to enhance the depth and validity of the data, aligning with Hennink et al. (2020) research on in-depth interviews as a data collection method for qualitative studies and using Ediriweera and Wiewiora (2021) study on *Barriers and enablers of technology adoption in the mining industry* as a reference, the study will employ the interview data collection method. The purpose of an interview is to allow the participant to reflect on their past and present experiences within a specific area of discussion, thus, throughout the process, the participants should be impartially encouraged to elaborate on their personal interpretations related to the study (Hunter, 2011). In the study, the author used semi-structured interviews, which allowed participants to share their experiences and perspectives on a range of topics, allowing the inquirer to gather in-depth insights.

Similarly, this research, seeks to obtain detailed and nuanced responses to derive an in-depth understanding of the study phenomenon and related subjects. Therefore, the interview protocol will be designed with an emphasis on the adoption of ADS and systems integration for data analytics and systems adjustment. An interview protocol serves as a guide for data collection and subsequent analysis (Hunter, 2011). By utilizing open-ended questions, the interviews will provide the flexibility to explore closely related subjects to the study that may emerge. This approach not only enhances the richness of the data collected but may also enable the study to draw insights from the related topics to the area of study.

3.4 Research Participants and sampling

3.4.1 Research Participants

The term “population” in research refers to the set or group of all the units to which the findings of the research are intended to be applicable. These units possess variable characteristic under study and are the entities for which findings of research can be realized (Shukla, 2020). In the context of this study, the total population is represented by the mining industry, with a specific emphasis on open-cast mining drilling operations in South Africa.

3.4.2 Sampling

According to Creswell and Poth (2018), sampling entails choosing individuals from total population for study purposes as well as generalizing as specified by the outcomes of the sample. The primary purpose of sampling is the selection of suitable participants (population) to enable the focus of the study to be researched (Whitehead & Ferguson, 2018). The authors add that the decisions related to sampling impact the nature and quantum of data collected.

According to Gaokgorwe (2023), a sample is a representative of the total population for the generalization of the research findings. Whitehead & Ferguson (2018) state that sampling in qualitative research is termed non-probability sampling, which unlike probability sampling used in quantitative research, does not involve randomization. That is, the participants of a qualitative study population do not have an equal chance of being selected.

The study adopted non-probability sampling. This approach involves intentionally or purposefully selecting participants based on attributes such as their experience in the mining sector, understanding of the drilling process, familiarity with mining technologies, and their capacity to influence and/or shape organizational strategy, all of which are related to the subject of the study. According to Gaokgorwe (2023) and Whitehead & Ferguson (2018), there are four main types of qualitative non-probability sampling: (i) Convenience sampling; (ii) Purposive sampling; (iii) Snowball sampling; (iv) Theoretical sampling. Given that the participants in this study were deliberately chosen based on qualities pertinent to the research study, the qualitative non-probability sampling adopted was purposive sampling. Whitehead & Ferguson (2018) define this sampling method as one where participants are recruited according to a pre-selected criteria relevant to the research questions or objectives.

3.5 Data Analysis and Interpretation Framework

The process of data analysis involves making sense out of text and image data (Creswell, 2009). The study will conduct ten (10) interviews and data from interview findings will be analysed using content analysis. According to Gaokgorwe (2023), content analysis involves quantifying the application of specific concepts, words, and phrases. Humble and Mozelius (2021), states that the content analysis describes a variety of analytic approaches, from impressionistic to very strict and systematic text analysis. The author adds that there are three different types of qualitative content analysis, namely, conventional content analysis, directed content analysis, and summative content analysis. The suitability of each is dependent on the problem being studied and the research purpose.

The study will adopt the model of data saturation, which refers to the point at which no new information emerges, and additional data collection only reinforces what has already been expressed (Saunders et al., 2017). Saunders et al., (2017) further highlight that collecting more data than necessary can raise ethical concerns, such as overburdening participants, while an insufficient sample size may compromise the validity of the study's findings. Hennink and Kaiser (2022) emphasize that qualitative research sample sizes should be determined by data adequacy. This principle asserts that a sample is appropriate if it is sufficiently large to answer the research questions and fulfil the study's objectives (Bwalya, 2024). In this study, data saturation will be considered achieved when no new themes, issues, or relevant subjects emerge, ensuring that the collected data is comprehensive and meaningful.

3.5.1 Methodological Transparency and Data Handling

Using the thematic method by Braun & Clarke (2021), interviews were used as a data collection method. Upon concluding the data collection process, the interviews were transcribed using MS Word. Upon detailed reading, the interview data was validated to enable for data coding and analysis thereon to be done using a qualitative software program known as NVIVO 15.

The codes were created by the software and the participants dialogue were then assigned to respective codes. Thereafter, analysis techniques, such as Word Clouds, Cluster analysis, Tree Maps and Word trees were used to determine frequency and commonalities and interpret the data, leading to the formulation of relevant primary themes and sub-themes. The primary themes were aligned to the interview questions and research objectives. The subthemes (which inform the primary themes) were 'inductive' as they are informed by what the dialogues reflected. These were further validated by a second round of analysis using the analysis techniques alluded to. Once the primary themes and subthemes were defined, hierarchy charting was used to determine the size and relevance of the themes.

This process ensured that the analysis underpinned the data and aligned with the study's objectives. By combining inductive coding with structured analytical techniques, the thematic outcomes reflect both the participants' experiences and the theoretical lens of the research. The use of NVIVO 15 as an analysis tool improved the transparency, reliability, and depth of the findings that form the basis for interpreting the dynamics of the adoption of autonomous drilling systems and subsequently using that insight to develop a framework guiding the seamless adoption and implementation of these systems in open-cast mining operations.

3.6 Potential Constraints and Challenges of the Study

This research is confined to open-cast mining, particularly its drilling operations. Therefore, the results of the study may not be fully applicable to other types of operations, such as underground mining.

Regarding **site X**, compared to other operations, it experiences a high turnover rate. With potential retrenchments on the horizon, the desired participants may not be available for interviews, or they may be new to the site. This could result in responses that are more general, lack a specific connection to **site X** and a percentage of the interviews being successful instead of the full ten (10) proposed.

3.7 Quality Assurance

Within qualitative research, two main strategies promote the rigor and quality of the research: ensuring the authenticity of the data and the trustworthiness of the analysis (Sargeant, 2012). The author expresses that these strategies are similar to ensuring validity and reliability in quantitative research.

3.7.1 Authenticity of the data

Sargeant (2012) describes authenticity as the quality of the data and the procedures used to collect it. The author adds by highlighting the elements to consider as follows:

1. Sampling approach and participant selection
2. Data triangulation
3. Appropriate data collection methods
4. Unbiased interview guides
5. Researcher relationships and bias

This study will utilize the non-probability sampling, thus, selecting participants with extensive experience in the mining industry, mining digital technologies & open-cast mining drilling. This approach was designed to address the research objectives of the study and ensure data collected is relevant by choosing participants who are knowledgeable about trends, culture, and technology adoption in mining.

Given the technical nature of the study, semi-structured interviews were chosen over other methods such as focus groups. Through this approach, the inquirer can ask open-ended questions to encourage comprehensive responses and can explore, in detail, the individual experiences and perceptions. Furthermore, the interview protocol will be designed to avoid leading or biased questions; thus, ensuring that participants can express their views openly, without being influenced by the way questions were framed.

3.7.2 Trustworthiness of the analysis

Trustworthiness pertains to the quality of the data analysis (Sargeant, 2012). The following elements can be considered when assessing the quality of analysis:

1. Clear description of the analysis process
2. Development of data codes and categories

3. Resolution of differences in findings

In the case of this research, the study in alignment with the data saturation model, with employ methodical categorization of participant responses. This exercise is aimed at assisting with establishing common themes and being able to identify repetition in the responses and filtering data systematically.

3.8 Ethical considerations

Particularly in research involving human participants, research ethics approval prior data collection is important (Fleming and Zegwaard, 2018). The critical areas of consideration as identified by Fleming and Zegwaard (2018), are as follows:

1. *Informed consent:* This area emphasizes the importance of ensuring that research participants are explicitly informed of what is expected of them by the researcher, as well as any consequences of their participation. Despite the one-on-one nature of the semi-structure interviews, it is important that participants understand how their shared information will be stored, utilized, and disseminated. For this study, interview participants will be asked to sign a consent form if they agree to participate. Furthermore, even if they decide to participate, the terms of participation will be clearly outlined, and they will have the freedom to respond only to those questions they feel comfortable with-there is no obligation to answer every question posed.
2. *Confidentiality and anonymity and Risk of harm*: For this study, the identity of the study participants will not be published nor will the name of the specific operation. Apart from the assurance provided to the study participants through the protection and withholding of their identities and not disseminating their responses haphazardly on platforms not initially agreed upon; consideration for the time they will dedicate to support this study is crucial. The researcher must respect that time and ensure that it does not affect their ability to deliver of their day-to-day tasks as that may impact their employment status if mismanaged. Therefore, participants will be informed that the interviews are recorded and that they will have access to transcripts upon request. In this manner, participants can be assured that their shared information will not be distorted

or misrepresented. Moreover, if interviews exceed the scheduled 60 minutes, the researcher will only proceed with the participant's consent. Otherwise, the participant is not obliged to continue at the expense of neglecting their daily tasks in the workplace.

3.9 Chapter summary

This chapter provides a detailed overview of the research methodology used to achieve the research objectives of the study. It adopts the interpretivism paradigm to understand the subjective experiences of individuals within this context. By utilizing a qualitative research strategy, the study uses semi-structured interviews for data collection, ensuring comprehensive and relevant insights. Experienced participants are chosen the purposive sampling approach and an inductive approach in data analysis, where content analysis is used to identify patterns and themes until data saturation is achieved. Additionally, the chapter discusses the key elements of quality assurance.

CHAPTER 4: THEMATIC ANALYSIS INSIGHTS

4.1 Introduction

This chapter provides a qualitative analysis of the key themes emerging from the research study, with an emphasis on their adoption, the associated challenges, and strategic application options in the mining industry.

Upon data collection, the interviews were transcribed using MS Word. Upon reading and validating the interview data, coding and analysis was done using a qualitative software program known as NVivo 15. Codes were created and participants interviews were assigned to the respective codes. For ease of reference, the primary themes were aligned to the research objectives; and the subthemes (which inform the primary themes) were 'inductive' in nature as they were informed by what the interviews reflected. After further analysis and data validation, hierarchy charting was done to determine the size and relevance of each emerging theme.

4.2 Participant demographics

The research participants included personnel at specialist, middle and senior management level. As alluded to in Chapter 3 (refer to 3.4.2- Sampling) of this report, participants were selected based on attributes as follows: experience in the mining sector, understanding of the drilling process, familiarity with mining technologies, and capacity to influence and/or shape organizational strategy. Seven (7) participants were interviewed, at which point of saturation had been reached. That is, data saturation was observed, as participant responses exhibited strong similarities, and no new information emerged that would contribute to new or additional themes. Subedi (2021) provides examples of various qualitative studies with participant numbers ranging from three (3) to ten (10), including "three-participant narrative inquiry (Wise, 2020), four-participant narrative inquiry (Bentley, 2021), five-participant narrative inquiry (Gao, 2021), seven-participant narrative inquiry (Bryant, 2021), eight-participant narrative inquiry (Tiffany-Kinder, 2020), and ten-participant narrative inquiry (Crawford, 2021; Magalhaes, 2019)."

Thus, given the established precedent in qualitative research, a study with seven (7) completed interviews meets the threshold for validity and provides sufficient data for analysis. The consistency in participant responses, along with the achievement of data saturation, ensures that the study has gathered adequate insights to draw meaningful conclusions.

An outline of the participants' demographics is provided in Table 5, which includes information on the participants' roles, departments, years of experience, education level, and industry knowledge. Professionals from the technology service providers and mining operations across various divisions, that is, mining extraction and mining technical services make up the population. This provides a diverse viewpoint on the use of autonomous drilling systems (ADS) in open-cast mining operations and eases the understanding of technological, operational, and strategic elements impacting the adoption and implementation of autonomous drilling systems in mining.

Table 5: Interview participant demographics
source: Author constructed, (2025)

Participant	Designation	Department	Years of Experience	Education Level	Industry Expertise
Participant 1	ADS Technician	Technology & Innovation *(Service Provider)*	8 years	BEng in Mechanical Engineering & Diploma in Instrumentation	Oil and gas Industry
Participant 2	ADS Supervisor	Technology & Innovation *(Service Provider)*	14 years	BSc in Mechanical Engineering	ADS Drilling Systems
Participant 3	Drill and Blast Engineer	Mining Technical Services	6 years	BSc Mining Engineering	Drill and blast design and execution
Participant 4	Geotechnical Specialist	Geotechnical	5 years	BSc Geology and Strata Control Certificate	Ground stability and support
Participant 5	Automation Specialist	Technology & Innovation	5 years	BSc Industrial Engineering and Advanced certificate in Industrial Automation	Fleet Management Systems
Participant 6	Section Manager Drill & Blast	Mining Technical Services	12 years	BSc Mining Engineering, Postgraduate diploma in Business Administration & MSc Mining Engineering	Drill & Blast technical and Mining execution
Participant 7	Drill and Blast Supervisor	Mining Operations	7 years	BEng Mining Engineering and Blasting certificate	Short- & Long-Term Planning

4.3 Qualitative techniques utilised

In qualitative research, data visualization techniques such as word clouds, tree maps, cluster analysis, and hierarchy charts are crucial for revealing relationships and patterns in the data (Verdinelli & Scagnoli, 2013). The authors add that these techniques help in presenting inferences and representing data in a summarised, simplified and/or transformed manner.

These visualization techniques are useful for efficiently communicating interview results and making the data accessible to both mining industry and non-mining audiences. The many visualization techniques available for qualitative research will be utilized to make connections and analyse the data. Below are some of the techniques used for this study:

4.3.1 Word cloud

Word Clouds are a visual representation of text data where the font size of each word implies its frequency or importance (Turner, 2017). They are particularly useful for identifying the most prominent terms in a dataset, providing an overview of the main themes discussed by participants. The word cloud in Figure 5 revealed that drilling systems, and technology, to name a few were the most frequently used terms across all emerging themes- indicating them to being the key processes and challenges requiring optimisation. Moreover, the terms relating to technology, such as “autonomous”, “ADS”, indicate the need for integration of technologies- all reflecting emphasis on the highlighted concerns needing to be addressed.

4.3.2 Cluster analysis

Cluster analysis involves grouping a set of objects (bubbles) in such a way that objects in the same group are more like each other than to those in other groups (Deressa & Choudhary, 2025). In qualitative research, this technique can be used to identify patterns and relationships within the data, helping to uncover underlying themes and insights (Miles, Huberman, & Saldana, 2014). Through clustering, the author was able to identify, for instance, factors that impact on drilling efficiency such as block preparation- allowing for a more targeted approach in establishing the implementation framework and overall optimization of the drilling process.

4.3.3 Tree Maps

Tree maps are a hierarchical visualization tool that displays data as nested rectangles (Miles, Huberman, & Saldana, 2014). Through the tree maps structure, one is able to explore the patterns within the data and visually display relationships between different elements.

4.3.4 Hierarchy Charts

Hierarchy charts show how the various themes and subthemes are related, revealing the most prominent theme or themes, and enabling a directed approach to data interpretation and analysis (Lumivero, 2025). The size of the nodes is reflected in the hierarchy chart, where a larger size indicates the most volume and/or concentration of responses in that area. For instance, the biggest node is associated with the objective of identifying and analysing the key barriers to digitalisation and automation of drilling operations in mining operations. This can be said to be the most concerning across the diverse participant insights, thus meaning it would probably require most focus and resources to address.

4.4 Qualitative analysis

This section presents the findings from participant interviews in line with the study propositions and stated study objectives. The key objectives are as follows:

- To evaluate the existing digital technologies used by mining companies.
- Identify and examine operational factors affecting the drilling process and implementation of autonomous drilling systems.
- Identify and analyse the key barriers to digitalisation and automation of drilling operations in mining operations.

In Chapter 3 *(Refer to 3.5 Data Analysis and Interpretation Framework)* of the report, the author indicated that content analysis will be used to analyse the data from the interviews. Shava, Hleza, Tlou, Shonhiwa, and Mathonsi (2021) define content analysis as a "research method for the subjective interpretation of data content through a systematic classification process involving coding and the identification of themes or patterns." The authors argue that nearly any form of communication material, such as narrative responses, open-ended survey inquiries, interviews, focus groups, observations, and printed media like books and articles, can be proficiently analysed by qualitative content analysis. Qualitative content analysis is often aided by computer programs like NVIVO and/or ATLAS.ti, which enhance the organization and efficiency of qualitative projects (Shava, Hleza, Tlou, Shonhiwa, & Mathonsi, 2021). These software solutions primarily enhance efficiency in data sorting, filtering, and pattern recognition within data sets. The objective was to identify key themes within the interview content and provide an accurate representation of the reality brought about by those themes as experienced by the participants within a particular setting. This process adhered to the basic principles of content analysis: preparation, coding, and interpretation of qualitative analysis results. The analysis aimed to check for any repetition and/or common sentiments to clearly assess data saturation.

4.4.1 Evaluating the existing digital technologies used by mining companies

This theme examined the current digital technologies present within the organisation as well as the impact such technology may have on operations

4.4.1.1 Autonomous Drilling Systems

Autonomous drilling systems (ADS) were highly mentioned whereby these served as control instruments that regulated parameters such as temperature, hydraulic, air and water pressure amongst various parameters on drilling equipment. These systems replaced human operators from the actual field operations to enhance safety and increase efficiencies during drilling operations. Furthermore, automated loading and hauling and planning technologies were widely utilised in mining operations such as dispatch fleet management systems (FMS).

Table 6: ADS digital technologies
source: Author constructed, (2025)

Theme	**Sub-theme**	**Comments**	**Participant Reference**
Digital Adoption	Real-time monitoring	"At Site X, we utilize cutting-edge digital technologies, including fleet management systems (FMS) that allow for real-time monitoring of equipment."	Participant 7
Autonomous Drilling System	Autonomous Drilling	" Autonomous Drilling System (ADS) control instruments which control parameters or variables such as temperature, hydraulic/air/water pressure, and level (more specifically in the oil & gas industry)"	Participant 1 & 2
		"Autonomous drilling system used to eliminate the use of human operators in the drilling process. This is aimed at improving safety within the drilling operations."	Participant 4
		"Most mines use automated drilling and hauling technology."	Participant 6

4.4.1.2 Existing mining technologies

It was evident that autonomous drilling was occurring and supported by numerous technologies. This was informed by the responses provided by the participants as noted in Table 7.

Table 7: Existing technologies
source: Author constructed, (2025)

Theme	Sub-theme	Comments	Participant Reference
Enabling technologies	Blast Logic	"Blast Logic: This server link technology is used to acquire post drilling data for validation and drilling design reconciliation post execution."	Participant 3
		"The other technology is Blast Logic, which is a technology used to check block view and dimensions of all drilled holes. Blast Logic is also used to verify and validate drilling information and enable release of production blocks to the blaster on time."	Participant 4
		"Blast Logic: Technology used for drill and blast monitoring, blast design and blast hole charging control."	Participant 5
	Mobias	"Mobias- a point-to-point network connected technology used in drilling equipment and dump trucks. It basically replicates or copies the actions of the engineer onto other units thus making it a good technology for continuous improvement and real-time problem resolution."	Participant 1 & 2
	Pro-vision and RFID	"Provision: Technology for monitoring and reporting on misfires and charge exclusion zones."	Participant 5
		"RFID tags for asset and human tracking in the mining industry. For humans, it forms part of their PPE as a barcoded strip on their	Participant 1 & 2

		garments and on machinery, it uses heat maps to clock machine position."	
	Drone technology	" (Use of) Drones for mine surveying."	Participant 6
	Predictive maintenance software	"Moreover, we incorporate predictive maintenance software (MineCare) combined with IoT sensors to enable early fault detection particularly on our P101 fleet. "	Participant 7
	Rockmar	Rockmar: This technology is merely a user interface for drill navigation systems, drill data capturing and analysis.	Participant 5
	Microstation	Microstation: Used for drill pattern design showing topography and location/drill hole coordinates. This design is exported onto the drill rigs to enable for drilling to design	Participant 3,4 & 5
	Flanders system	Flanders system: This is the system for autonomous drilling, and it uses csv files for inputs. The downfall is that the system can be overridden which means its only used as an option not the standard.	Participant 3
		Flanders: This technology is used for autonomous drilling to ensure accurate drill navigation and drilling activity data capture. The only limitation with this technology is that no more than one person can be on the user interface especially during a drilling activity because if one switches to a different screen, it affects the operators view as well.	Participant 5

4.4.2 Identification and examining of operational factors affecting the drilling process and implementation of autonomous drilling systems

The efficiency, accuracy, and safety of drilling operations have significantly improved because of the use of digital technologies. However, both operational difficulties and technical capabilities have influenced the adoption, especially in the areas of technology implementation, approval, and vetting. The key themes and subthemes that emerged from participant interviews are summarized in Table 8, which also highlights the benefits, limitations, and overall impact of these technologies and/or innovations on the implementation of autonomous drilling systems (ADS).

Table 8: Factors impacting ADS implementation
source: Author constructed, (2025)

Theme	Subtheme	Keywords	Comments	Participant Reference
Impact of Digital Technologies on Efficiency and Productivity	Quality Control			
		Improved Drilling Quality	"Blast Logic enabled proactive correction of substandard drill holes"; "MicroStation simplified drill pattern design and improved accuracy"	Participant 4, Participant 5
		Block Design	"Blast Logic allowed engineers to design blocks based on actual ground conditions rather than ideal setups"	Participant 5
		Drill Verification & Measurement	"Verification of planned drill meters against actual drilling progress was enabled"	
		Continuous Improvement	"Data analysis enabled evaluation of fragmentation to validate and	Participant 3

			understand blast outcomes"	
	Drilling Efficiency			
		Improved Response & Turnaround Time	"Mobias improved exception management"; "RFID tags improved response time to breakdowns"; "quicker block movements increased productivity"	Participant 1, Participant 2, Participant 4, Participant 5
		Minimised Downtime	"Technologies reduced internal delays, ensuring continuous drilling operations"	Participant 1, Participant 2, Participant 7
		Overall Efficiency & Productivity	"Operations effectively using technology showed improved efficiency and productivity"	Participant 6
	Monitoring & Safety			
		Health & Safety	"Technologies reduced operator exposure to dust and shaking conditions"; "proactively alerted teams to misfires"	Participant 1, Participant 2, Participant 4, Participant 5

		Monitoring & Security	"Employee tracking improved unauthorized operator identification and HR tracking"	Participant 1, Participant 2
		Visualisation & Identification	"Operators could view approved and drilled areas, aiding in socket identification"	Participant 4
	Effective Problem Solving			
		Real-Time Problem Resolution	"Improved network connectivity resolved issues of delayed failure management due to paperwork"	Participant 3
		Remote Resolutions	"Engineers accessed data remotely to resolve production block availability issues and ensure activity continuation"	
	Maintenance & Sustainability			
		Increased Component Life	"Autonomous Drilling Systems prolonged component life by operating within OEM-suggested limits"	Participant 1, Participant 2
		Cost Control	"Improved inventory management led to fleet optimization and cost savings"	Participant 1, Participant 2, Participant 7

4.4.3 Identification and analysis of the key barriers to digitalisation and automation of drilling operations in mining operations

This section highlights the primary barriers to Site X's adoption of digital technologies and ADS implementation. The participants' insights and developing themes are shown in Table 9.

Table 9: Key barriers to digitalisation & automation of drilling operations
source: Author constructed, (2025)

Theme	Sub-theme	Comments	Participant Reference
Integration and compatibility	System compatibility	"The systems themselves in their nature are disintegrated and thus we cannot verify or fix the system failures on the other for instance"	Participant 4
		"The compatibility of the of the systems. E.g., in the Fleet management space, the Komatsu trucks come modular-ready and Cat trucks come Mineware ready. Therefore, getting Dispatch into CAT trucks comes with an interface extra cost similarly getting the Mineware into the Komatsu trucks comes with an interface extra cost"	Participant 6
		"The challenges of integration encompass compatibility problems with outdated systems"	Participant 7

		"Achieving smooth communication between new autonomous systems and established manual operations has necessitated considerable calibration and modifications- which we are yet to say we're fully comfortable with"	
		"The difficulties associated with modifying existing equipment without tempering with the existing systems especially those relating to critical controls"	
	File incompatibility	"The biggest challenge is the fact that files from microstation can read as invalid when exported to Blast Logic for example. File naming and data representation format differ from one technology to the next"	Participant 4
		"We encounter file conversion issues. For instance, vipers use csv files, but the small drill use a different system that doesn't read such files"	Participant 5
Data Analytics	System coding limitation	"Despite these advancements, we encounter challenges in fully exploiting the generated data due to issues with data integration and analytics capabilities, which impair decision-making and limit the	Participant 7

		extent to which we apply technology for operational and systems improvement”	
		“System language/coding limitations: the differing formats allow for human error to be a bottle neck”	Participant 3
		“The process owners including drill operators have no coding understanding and thus this may limit progress as external support delays”	
	System versus drill type	“The Flanders system has HPGPS on the mine vipers (215mm drills) and not on the small (165mm) drills”	Participant 5
Technology overlap	Limitations on design and safety	“Software limitations on user access and inaccessible software and system version updates: This leads to multiple drill designs with various stakeholders thus making it difficult to manage design versions, inhibiting proactive problem-solving and posing a safety risk due to for example, unknown/unconfirmed socket positions”	Participant 3
		“We also have multiple technologies performing the same activities”	Participant 5
Workforce skills and training	Lack of training and induction	“When new employees start, they are not inducted on the	Participant 1 & 2

		system and there's a general lack of training"	
		"Also, the business hasn't shown interest in investing on training its personnel"	Participant 3
		"We experience skills limitation/shortfall due to the lack of training programs in the drilling space"	Participant 5
	Fragmented and non-inclusive training	"The other limitation is that drill operators are trained on the drilling activity itself and the back-end levers/enablers that support the process, e.g., laser clean-up to allow for continuous operations is a responsibility for the engineer (Service provider) instead of the drill machine operator. Such creates unnecessary breakdowns as well as delays that can easily be avoided"	Participant 1 & 2
		"We propose that operators be trained to be at similar level as Service provider technicians so that the end-user has in-depth knowledge of the system and can use it to its max potential and be able to report on technical mishaps or shortfalls with confidence"	
		"Lastly, the lack of involvement of operators in activities such as	

		root cause analysis and lack of uniformity on drilling standards from one operator to the next pose limitations to full implementation of ADS systems”	
		“Training and retraining to ensure that people skills grow and transform with the ever-changing operational conditions. With that said, we currently lack such routines and that limits our ability to fix minor issues or implement minor changes because each task belongs to a certain individual- if operators can be upskilled, they can be enabled to act on or resolve simpler tasks such as opening a csv file and making changes on it as and when needed”	Participant 3
	Lack of specialised training and Inconsistent routines	“With training requirements, ADS operators are trained by the service provider, but the challenge is that the training deteriorates as there is no set routine for retraining and frequent sharing of information on system changes/upgrades”	Participant 1 & 2
		“Also, the mine has simulator cabins for dump trucks and shovels but none for drills. That indicates just the focus and	Participant 5

		investment into getting the mine to drill autonomously across all pits and on a day-to-day basis instead of as and when the section manager feels like it"	
		"Challenge is the OEM special skill required to manage the maintenance of these technologies. Most mines do not have the in-house training and skills to install and maintain the Autonomous technology. Companies tend to outsource the skill from the OEM which comes at an extra cost"	Participant 6
	Limited Problem-Solving Capacity	"By promoting operators without technical know-how into roles such as those of operating ADS poses a limitation on problem-solving capacity"	Participant 3
Organizational structure	Employee turnover	"The other big challenge is the turnover rate at the mine, several employees leave the business"	Participant 1 & 2
	Lack of KPIs	"Lastly, there are no specific KPIs being measured and controlled thus no routine task observations occur for the purpose of improvement and process control"	
	Hierarchical exclusion	"Operationally, we've observed hierarchical behaviour and with that attitude, we are excluded	

		from routines where we can collectively discuss system updates and other mechanical work needed on the units to avoid clashes with day-to-day plans"	
	Resistance and change	"The lack of trust and transparency with the mine looking for imminent results which limits trust relationships because of previously failed investments and service providers overpromising and not delivering results (also limits opportunity for further investment)"	Participant 1 & 2
		"Technology mistrust especially from novice operators who feel that it may limit their way of work and take away their decision-making power"	Participant 3
	Change management process	"Lack of a change management process which affected the implementation of autonomous drilling systems from inception"	Participant 1 & 2
	Support and investment	"There's lack of financial investment particularly for system upgrades which then limits progress (especially critical in an ever-changing environment)"	
Access and system control	Network and connectivity	"The biggest barrier is the network coverage in our pits.	Participant 5

		We struggle with connectivity and that inhibits autonomous drilling”	
	System overrides	“On Flanders system, the service provider is the only person that can access the system. It has no user interface thus delays decision making because of manual interface required”	Participant 5
		“We are constantly experiencing challenges in the operation resulting in the numerous system override incidences which in reality, are not acceptable as they hinder progression in the implementation of these technologies and may lead to fatal incidents if allowed to continue so”	Participant 7
Cybersecurity		“Furthermore, navigating regulatory requirements especially that pertaining to cybersecurity for interconnected systems present considerable challenges because as is, the controls are not as robust as expected especially since there are external service providers involved on a day-to-day basis”	Participant 7
		“In the implementation of autonomous drilling systems,	Participant 7

		we fell short on the systems control because as a business, we don't have access to our own data generated by these drills, yet the service provider has access to our drives and database without limitations"	
Lack of systems knowledge		"The business does not have a technology champion and thus no due diligence is conducted prior to implementation of most technologies which results in us not realising the full value of it or worse, the technology serving no purpose of value to the business"	Participant 5
		"Furthermore, there's a lack of knowledge of the system itself, even by area section managers, which exacerbates costly behaviours such as equipment damages and increases callouts which directly links to overtime hours to service providers"	Participant 1 & 2

4.5 Chapter summary

The qualitative analysis of the technologies that exist in the mining operation indicates a significant transition to data-driven decision-making and automation. According to Grobbelaar & Bisschoff, (2022), highly data-driven organizations are three times more likely to report significant improvements in decision-making compared to those who rely less on data. Operational efficiency, safety, and productivity have been substantially improved through the introduction of technologies such as Autonomous Drilling Systems (ADS), fleet management systems, Blast Logic, and predictive maintenance software

(Minecare). These technologies, to the extent of their use in our operations, have streamlined drilling accuracy, optimized planning, and improved real-time monitoring, ultimately contributing to cost control and sustainable mining practices. Innovation plays a critical role in the mining industry as a tool to improve the efficiency of its processes, to reduce costs, but also to meet the increasing social and environmental concerns among communities and authorities (Burgess-Limerick, Horberry, Lynas, Hill, & Haight, 2025) and (Sánchez & Hartlieb, 2020).

However, while the adoption of digital solutions has proven beneficial, significant challenges that hinder full implementation of such technologies as ADS persist. System integration and compatibility issues, particularly between traditional manual systems and newly introduced technologies, continue to hinder seamless digital transformation. The findings of the interviews with diverse participants indicate a progression toward a digitally mining ecosystem. Young and Rogers (2019) emphasize that a review of digital transformation in mining reveals the importance of addressing integration challenges to achieve operational efficiency and safety, hence, in the context of this study, to fully unlock the potential of ADS in drilling operations, it is necessary to address the issues that are evident from the insights of the interview participants in a meticulous and strategic manner.

CHAPTER 5: Framework for implementing autonomous drilling systems in open-cast mining operations

This chapter aligns with the study objective of establishing a framework for the adoption and deployment of Automated Decision Systems in open-cast operations. The framework, as seen on Table 10 is constructed based on the findings of participant interviews and existing literature.

Table 10: Framework for adoption and implementation of ADS in open-cast mining operations

source: Author constructed, (2025)

Objective	Autonomous Drilling Technologies	Operational Factors	Key Barriers	Mitigation Strategies
Existing digital technologies used by mining companies in autonomous drilling	- Autonomous drilling systems (ADS) (e.g., Sandvik automine, Epiroc Pit Viper) - AI-Powered drilling control software (Flanders) - Automated drill bit wear monitoring - Remote operations & control centres - Lidar & GPS-based precision navigation - Real-time data analytics & reporting	- System compatibility with existing tech stack - Data integration with mine planning & predictive maintenance systems - Automated & immutable safety controls & intervention - Equipment uptime optimization through predictive maintenance & simulator training	-Traditional & non-standard drilling systems limiting integration - High & continuous capital investment requirements for system upgrades -Cybersecurity risks & data governance challenges - Limited connectivity in remote mining pits & regions	- Thorough due diligence & feasibility studies for technology preparedness to allow for a phased deployment to minimize disruption & manage costs & expectations on results. - Adoption of communication protocols and standardized data formats - Adoption of strong cybersecurity standards and real-time monitoring

				- Implementation of private LTE or 5G networks and edge computing for data processing
Operational Factors Affecting the Drilling Process and Implementation of Autonomous Drilling Systems	- Automated drilling pattern optimization - Real-time rock mass analysis (laser scanners) - Sensor-based drill hole deviation correction - Hydraulic pressure, oil, water levels, torque, and RPM monitoring	- Workforce reskilling & training for system operation, troubleshooting & maintenance - Variability in rock conditions affecting drilling accuracy and drill design compliance - Alignment of ADS with short-term & long-term mine planning digital tools/software - Standard drill design uploads	- Operator resistance due to fear of job loss and decision-making displacement - Skills gap in utilising advanced automation & AI-based systems - Geotechnical uncertainties (formations) impacting drilling accuracy - Need to optimize drilling time and frequency - Need to control limits to prevent premature equipment damages.	- Targeted and tailored upskilling & workforce transition programs - Automated function for adaptability to variable rock conditions (drill rate adjustment, angled holes, hole length compliance) – Value chain activity real-time communication, e.g., geotechnical feedback rock movement/formation warnings - Standardize reporting and formatting protocol to eliminate having multiple block designs for one block. - Employ sensors with alarm warnings/triggers for timely response to equipment faults.

Objective	Autonomous Drilling Technologies	Operational Factors	Key Barriers	Mitigation Strategies
Key Barriers to Digitalisation and Automation of Drilling Operations	-Edge computing for drill data processing -Integration to Predictive Maintenance for Drilling Equipment MineCare). - Digital Twins for system and drilling operation simulation & testing - Software licencing & upgrades	- Adherence to regulatory requirements - Proving ROI - Ensuring ADS aligns with broader mining automation strategies - Addressing licensing protocols	- Regulatory uncertainty - Unclear return on investment (ROI) projections - Reduction of equipment damages and premature wear on critical spares - Opposition from labor unions & employees - Understanding licencing requirements & renewal periods.	- Alignment with key regulatory bodies to fast-track needed approvals & get guidance on correct proceedings - Pilot studies and trials to showcase efficiency gains & deter cost benefits - Transparent engagement with workforce & stakeholders - Adoption of environmentally friendly automation practices (e.g., reduced emissions, energy-efficient designs)

5.1 Integrated TOE-DOI model: Thematic connections

Thematic analysis was applied within the integrated TOE-DOI integrated framework to interpret participant responses, thereby enhancing the explanatory power of the findings, and identifying consistent adoption patterns across technological, organizational, and environmental domains.

By showing how different technological, operational, and external factors influence the adoption of autonomous drilling systems, the framework for implementing these systems in open-cast mining operations is in line with the integrated Technology-Organization-

Environment (TOE) and Diffusion of Innovation (DOI) model. From a technical standpoint, the framework identifies important technologies that can be used, including real-time analytics, LiDAR-based precision navigation, and AI-powered drilling control software. Site X would need to evaluate how much these innovations enhance productivity and integrate with the current tech stack and infrastructure, as they align with DOI's relative advantage and compatibility features. The complexity feature of DOI is highlighted by the fact that traditional systems are still typically used and that new ones require significant capital expenditures for implementation and upkeep. Participants from diverse operational roles at Site X voiced concerns about system compatibility and possible disruptions to current workflows, highlighting the fact that even though the technology is marketed as cutting edge and will therefore simplify work processes, these perceptions remain a challenge and call for careful implementation and effective change management techniques.

Key adoption factors, including stakeholder engagement, regulatory constraints, and workforce adaptation, are addressed by the TOE framework on the organizational and environmental fronts. Organizational resistance emphasizes the cultural and skill-related barriers to adoption, especially among drill operators and maintenance personnel. Some participants expressed doubt about job security, which is consistent with DOI's feature of observability, which holds that resistance to change arises from the obvious and recognized effects of automation on employment. In order to prevent implementation delays, Site X needs to make sure that autonomous drilling adoption is in line with all mining regulatory frameworks, in order to address any regulatory uncertainties and sustainability concerns.

The drilling operators may underestimate the learning opportunity presented by accepting the change in their traditional work, and technology providers may overstate ROI timelines to gain backing from technology champions. This could lead to bias and affect the mine's ability to make well-informed decisions and win over its operators so that they can also invest in the implementation and ongoing improvement of ADS in the drilling operations. According to the suggested framework, Site X and other mines that might utilize it should monitor the adoption and implementation of ADS over time to validate the results and provide suggestions for improvements.

5.2 Reflection on limitations

This section outlines the topmost limitations of the study to give an indication of the constraints and any potential biases that may affect the interpretation and applicability of the study findings. The limitations are as follows:

- Generalisability of study results

The findings of this study are not generalisable beyond the specific context in which the research was conducted. This limitation occurs because the sample may not be representative of the broader population, and the study conditions differ significantly from other settings (Murad, Katabi, & Montori, 2017). Murad, Katabi, & Montori, (2017) further state that generalisability is a common challenge in research, particularly when the study sample is not randomly selected or is too small to represent the larger population.

- Subjectivity of human perception

The study relied on human perception, which is intrinsically subjective and is shaped by individual emotions and biases. This subjectivity can influence the consistency and reliability of the data collected, as human emotions and perceptions may significantly among participants during interviews, and subjective experiences are difficult to quantify and standardize (Brown, 2019).

- Context-specific environment

The study was conducted in an open-cast mining environment, which may limit applicability of the findings to other industries and/or different mining environments such as underground mining. The distinctive operational conditions of open-cast mining and the drilling methodology may not be directly transferable to other contexts, thereby restricting the broader applicability of the study results.

CHAPTER 6: CONCLUSIONS

This study examined the optimisation of surface mining drilling techniques by means of digital methods, employing an interpretivism paradigm to assess the technological, organizational, and environmental elements that affect implementation. The integration of the diffusion of innovation (DOI) theory and the TOE framework provided a structured approach to understanding the intricacies associated with autonomous drilling systems. Results show that although digital mining solutions can improve efficiency, lower operational costs, and enhance safety, challenges such as legacy systems, regulatory constraints, workforce adaptability, and technological readiness need to be addressed. This study systematically evaluated these factors, thus adding to the knowledge base of the industry and providing actionable insights for mining houses, particularly those who practice surface mining, aiming to optimise its drilling operations.

Future research might include comparative analysis across various mining operations and regions to increase reach and obtain extensive insights into the elements influencing the adoption and implementation of ADS. Additionally, investigating the relationship between AI, ML and ADS can potentially further advance the drilling space. This is backed by an article on Halliburton, (2025), which highlights that "autonomous drilling denotes the integration of artificial intelligence to revolutionize drilling operations and enhance performance in areas traditionally reserved for human intelligence." According to Epiroc, (2024), "change must be strategic, holistic, and personal. The transformation of a mining business must be supported first by top management, to increase the chance of employee buy-in." Hence, diving deep into change management strategies and tailoring them to the mining industry is seen as being central to addressing any human and organizational related barriers to the implementation and further advancement of ADS.

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APPENDIX A: Participant information sheet

Dear Sir/Madam

My name is Nomcebo Mlotshwa, and I am a student in Master of Management in Digital Business at the University of the Witwatersrand Business School. My research is supervised by Dr Michael Sony, Senior Lecturer: Digital Business | Wits Business School. I am conducting a study titled Optimizing Open-Cast Mining Drilling Processes through Digital Mining.

I would like to invite you to participate in a semi-structured interview as part of this research study. The purpose of this interview is to gather insights into the current use of digital technologies in mining, understand operational factors affecting drilling processes, identify barriers to digitalization, and develop a framework for the effective adoption of ADS in open-cast mining operations.

If you decide to part-take, the participation details are as follows:

- The duration of the interview is set to last approximately 60 minutes.
- The interview will be conducted online at a time convenient for you (will be discussed and set well in time)
- During the interview, I will ask questions about your experiences and perspectives related to digital technologies and autonomous drilling systems.

In the case of confidentiality and anonymity, please be advised that your participation will be confidential. Any information you provide will be anonymized, and your identity will not be revealed in any reports or publications. Also, the interview will be recorded for accuracy, but recordings will be kept confidential and used solely for this research.

Participating in this interview is on a voluntary basis. You will not be compensated for any information shared and it will not have an effect on your current employment condition. Therefore, you may choose to withdraw from the study at any time without any negative consequences. Additionally, you are allowed to only respond to the questions that you feel comfortable with.

While there are no direct benefits to you for participating, your insights will significantly contribute to developing practical strategies for integrating ADS in mining operations and will contribute to existing research.

Following the conclusion of the interview process, the findings of this study will be compiled into a research report, which will be available through the university library. If you would like a summary of the report, I would be happy to provide one. Moreover, should you have any questions, need clarity, or wish to provide more information in line with the study during and post the interview further, please do not hesitate to contact me the contact details provided.

For any ethical concerns surrounding this research, you may contact the University Human Research Ethics Committee at +27 11 717 1408.

Thank you for considering participation in this study. Your input will be highly valuable

Yours sincerely,

Research owner:

Nomcebo Mlotshwa

688368@students.wits.ac.za

Mobile: +27 72 187 8421

Research supervisor:

Dr Michael Sony

michael.sony@wits.ac.za

APPENDIX B: Participant consent form

Title of project: Optimizing Open-Cast Mining Drilling Processes Through Digital Mining

Name of researcher: Nomcebo Mlotshwa

I, ……………………………………..., agree to participate in this research project.

I agree to the following:

(Please circle the relevant options below)

The research study was explained to me.

I understand what this study is about. YES NO

I understand that I can volunteer to take part in the study YES NO

I agree that the interview activity may be audio recorded YES NO

I agree that direct quotations from my interview may be used by the researcher in their research report YES NO

I agree that my participation will remain anonymous (my name or other identifying data will not be used by the researcher in their research report) YES NO

I agree that other researchers may use the information I provide in my interview (depending on their own ethics clearance being obtained) but my name and any personal information will not be used or passed on. YES NO

Participant:

…………………(signature)…………………………………. (name)………………… (date)

APPENDIX C: Interview Protocol for semi-structured interviews

Research Purpose and Introduction

As part of my master's research for the study on the adoption and implementation of autonomous drilling systems (ADS) in open-cast mining operations, I am conducting interviews to gain insight on the drilling process and the factors influencing the integration of digital technologies in the mining sector. The purpose of this study is to evaluate the existing digital technologies used and identify operational factors and barriers affecting the drilling process.

The intended outcome of the study is to develop a strategic framework to facilitate the adoption and implementation of ADS, which can be used in the mining industry, specifically, open-cast settings to ensure systems integration and effective utilization in order to leverage on the benefits of ADS fully.

The purpose of this interview is to gather your insights, experiences, and perspectives on the use of digital technologies and the challenges associated with implementing ADS in open-case mining. Your input will be invaluable in identifying key operational factors, barriers to digitalization, and strategies that can help improve the integration of autonomous systems in mining operations. The interviewer will ask open-ended questions to allow for flexibility in responses and capture any ideas and thoughts as they relate to digital mining.

The interview will follow these steps post the introduction:

Interview Question: I will ask a series of questions designed to explore your views on current digital technologies, operational challenges, and barriers to automation within the context of autonomous drilling systems. These questions are meant to prompt detailed discussions and help me understand your perspective on these issues.

Confidentiality: Please note that the interview will be recorded for accuracy, but the recordings will be kept strictly confidential and used only for this research. Detailed notes will also be taken to assist with data collection.

Anonymity: All information collected will be handled with the highest level of confidentiality. Personal identifiers will not be used in the documentation, and neither the company nor the specific mining operation will be named in any reports or publications.

Please feel free to initiate an open discussion following the structured questions, as it can prompt more ideas and thoughts.

Thank you for your time and willingness to share your expertise. Your participation is most valued.

Table 11: Semi-structured interview protocol
Source: Author constructed

NO.	Research Objectives	Interview Questions
1	To evaluate the existing digital technologies used by mining companies.	1. Can you describe the current digital technologies being utilized in your mining operations?
		2. How have these digital technologies impacted the efficiency and productivity of your operations?
		3. What challenges have you encountered in integrating these digital technologies with existing systems and processes?
2	Identify and examine operational factors affecting the drilling process and implementation of autonomous drilling systems.	4. What operational factors do you consider most critical in the drilling process?
		5. How do these factors influence the implementation and performance of autonomous drilling systems?
		6. Can you provide examples of how operational challenges have been addressed or mitigated during the implementation of autonomous drilling systems?
3	Identify and analyse the key barriers to digitalisation and automation of drilling operations in mining operations.	7. What are the main barriers your company has faced in the digitalization and automation of drilling operations?
		8. How do regulatory requirements and compliance issues impact the adoption of digital and automated drilling technologies?
		9. In what ways do workforce skills and training requirements pose challenges to the implementation of autonomous drilling systems?
4	Develop a framework providing strategic guidelines to mining companies for seamless adoption and implementation of autonomous drilling systems in open-cast mining operations.	10. Based on your experience, what strategic guidelines would you recommend for the successful adoption of autonomous drilling systems in open-cast mining?
		11. How can mining companies effectively integrate autonomous drilling systems with their existing technological infrastructure?
		12. What measures can be taken to ensure the sustainability and continuous improvement of autonomous drilling systems in open-cast mining operations?
5	Closing	Please feel free to initiate an open discussion on ideas related to the study.

Steps to Follow:

Before we conclude this interview, please note that during and post compilation of everything shared in the interview, I may have follow-up or clarity-seeking questions to support my data analysis.

Everything from this interview has been captured in full and truthfully and should you wish to access the final report, it will be shared with you as needed.

APPENDIX D: Qualitative Analysis techniques

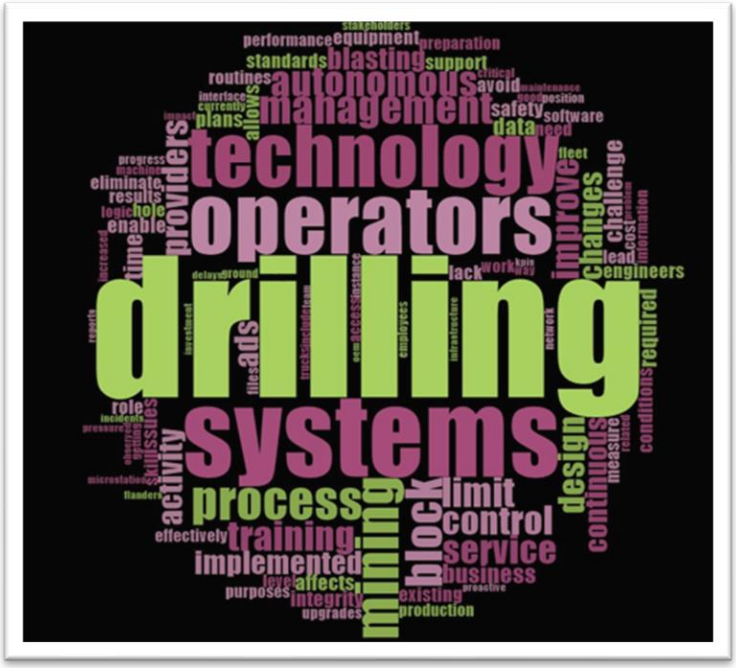

Figure 5: Word Cloud (All themes)
source: (Lumivero, 2025)

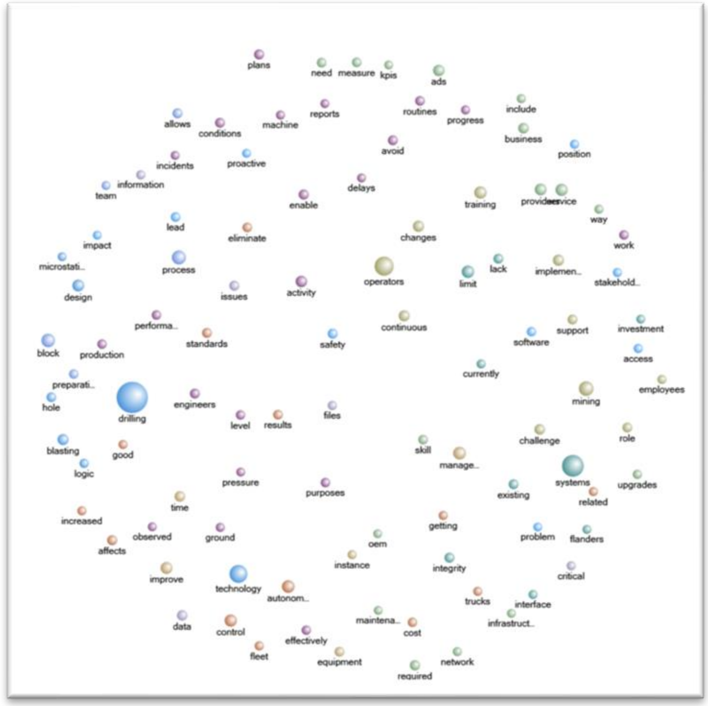

Figure 6: Cluster Analysis (All themes)
source: (Lumivero, 2025)

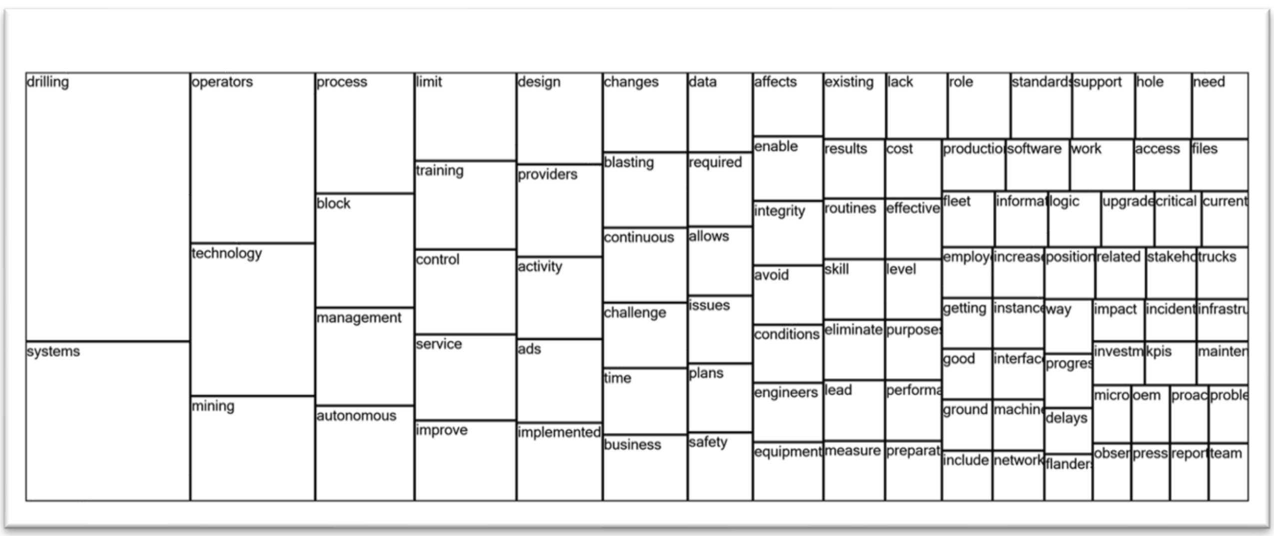

Figure 7: Tree Map (All themes)
source: (Lumivero, 2025)

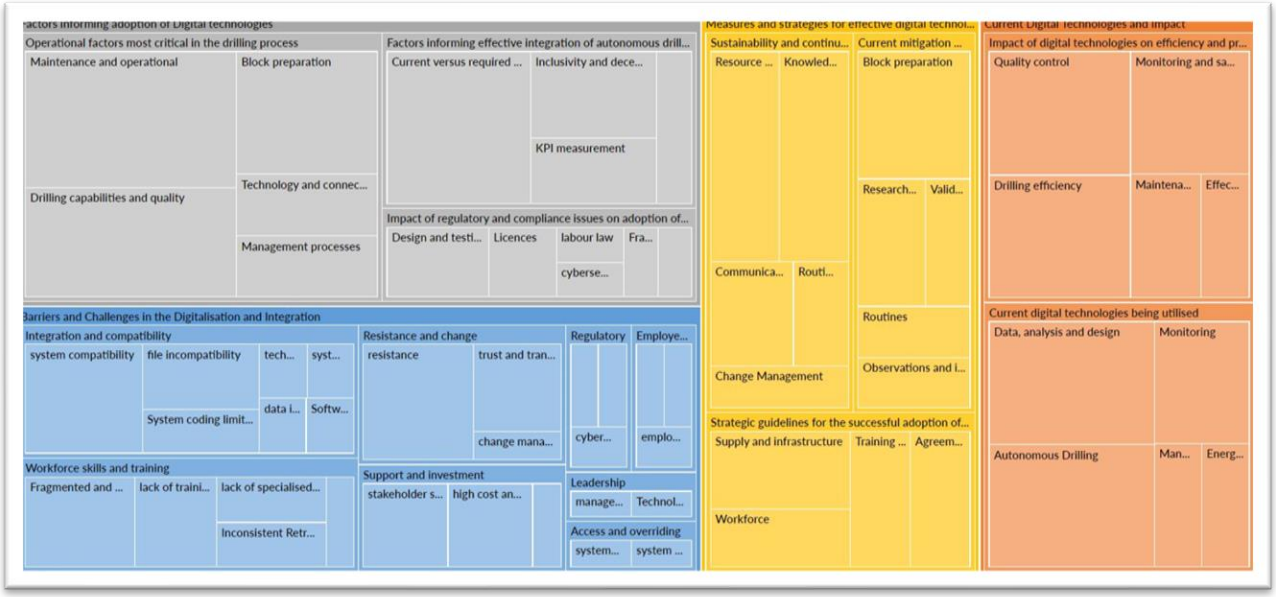

Figure 8: Hierarchy Charts (All themes)
source: (Lumivero, 2025)

APPENDIX E: Research permission letter

[OFFICIAL]

AngloAmerican

IRON ORE
KUMBA IRON ORE
Sishen Iron Ore Company (Pty) Ltd
KOLOMELA MINE

MEMO

SECURITY CLASSIFICATION

To	R Van Wyk, Manager P&O, Kolomela Mine T Mushi, General Manager, Kolomela Mine
From	NM Besnaar, Talent Advisor, Kolomela Mine
Date	19/07/2024
Enquiries	NM Besnaar, Talent Advisor, Kolomela Mine
Subject	Request to conduct research at Kolomela Mine: Nomcebo Mlotshwa 6230940.

1. **Purpose**

The purpose of this memorandum is to request approval for Nomcebo Mlotshwa to be granted an opportunity to conduct research project at Kolomela Mine.

2. **Background**

Nomcebo is a bursary holder at Kolomela Mine and currently a student WITS School, studying towards her Master of Management in Digital Business. As part of her studies, she has a research project that needs to be completed. For this study, data needs to be gathered from the company. A qualitative study which comprise of interviews and questionnaires will be used and the target population is as follows:

- Section Managers
- Service providers of auto drill systems

Topic of Research: The optimization of the drilling process in surface mines through the adoption and implementation of autonomous drilling systems

3. **Recommendation**

It is recommended that Nomcebo Mlotshwa be given an opportunity to successfully complete his research at Kolomela Mine.

Recommend/ Not Recommend	**M Besnaar** **Talent Advisor**	**Date** **19/07/2024**

[OFFICIAL]

Subject Request to conduct research at Kolomela Mine. Nomcebo Mlotshwa 6230940

Approval/ Not Approved **R Van Wyk**
Manager HR
Kolomela Mine
Date

Comments:
Not during working hours. Not to interfere with Production.

p.p
Approval/ Not Approved **T Mushi**
General Manager
Kolomela Mine
22/07/2024
Date

Comments:

APPENDIX F: Ethics Clearance certificate

[OFFICIAL]

Graduate School of Business Administration
University of the Witwatersrand, Johannesburg

Wits Business School Ethics Committee
Constituted under the University Human Research Ethics Committee (Non-Medical)

Ethics Clearance Certificate

Ethics protocol number: WBS/DB688368/716

This certificate is only valid with a legitimate ethics protocol number and signed by the Researcher (below).

Project title	Optimising open-cast mining drilling processes through digital mining
Investigator / Researcher	Miss Nomcebo Mlotshwa
Nature of Project	MM (Digital Business)
Decision of the Committee	Approved, provided stakeholders and participants are guaranteed confidentialty.
Issue Date of Certificate	02/09/2024
Expiry date	Date of submission of the project / research report
Chairperson	Dr Ayanda Magida ☎ +27 11 717 3953 ayanda.magida@wits.ac.za

Declaration by Researcher

One copy must be signed by the Researcher and returned to the Chairperson of the Wits Business School Ethics Committee.

I fully understand the conditions under which I am authorized to carry out the abovementioned research and I guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I undertake to resubmit the protocol to the Committee.

Signature

04.09.2024
Date: