



THE IMPACT OF INNOVATION IN THE COAL MINING INDUSTRY IN SOUTH AFRICA

by

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**A research report submitted in partial fulfilment of
the requirements for the degree of**

MASTER OF BUSINESS ADMINISTRATION

in the

**Faculty of Commerce, Law and Management
University of Witwatersrand**

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February 2025

DECLARATION

I, Mmboneni Dzimbae, declare that this research article 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 Business Administration in the Graduate School of Business Administration, University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other university.

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ACKNOWLEDGEMENTS

I would like to thank Wits Business School for giving me an opportunity to be part of the MBA programme. Thanks to all the lecturers and support staff of WBS for guiding me throughout my time in the programme. I would like to express my sincere gratitude to everyone who contributed to the successful completion of this research report.

First and foremost, I extend my deepest appreciation to Dr Roselyne Cheruiyot, whose invaluable guidance, constructive feedback, and continuous support played a crucial role in shaping this study. Her insights and expertise greatly enriched my research.

Furthermore, I am grateful to the survey respondents, for their time and willingness to participate in this study, providing essential data and perspectives that strengthened my findings.

Lastly, I am deeply thankful to my family, my wife, my children, employer for the supportive structure during the good and tough times and my friends for their unwavering support, patience, and encouragement, which kept me motivated throughout this journey., employer for the supportive structure during the good and tough times and my friends for their unwavering support, patience, and encouragement, which kept me motivated throughout this journey.

ABSTRACT

The South African coal mining industry is an important part of the country's economy, providing jobs and energy. However, the industry faces increasing environmental and legal challenges. To address these issues, companies are using new technologies such as artificial intelligence, the Internet of Things, robotics, and hybrid energy systems. This study examines how these technologies impact the industry's productivity, environmental protection, and social and economic conditions. It combines real-world data with academic theories to understand both the benefits and difficulties of these changes.

The study finds that while technology has improved efficiency, safety, and environmental management, there are still major challenges. These include high costs, difficulties in training workers, and problems with monitoring systems. The research highlights the need for better training programmes to help workers learn new technical skills. It also recommends using automated monitoring systems to improve environmental protection.

The study concludes that new technologies can greatly improve South Africa's coal mining industry. However, success depends on finding the right balance between modernizing operations, protecting the environment, and ensuring fair treatment of workers and communities. Government policies, industry cooperation, and investment in worker training will be key to making these changes successful. Future research should include more data analysis to measure long-term trends in the industry.

Keywords: artificial intelligence, coal mining, sustainability, technological innovation, workforce adaptation

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LIST OF ACRONYMS

AI	Artificial intelligence
FULCO	Full Calendar Operations
GDP	Gross Domestic Product
GIS	Geographic Information System
IoT	Internet of Things
NT	New technology
RBV	Resource-Based View
TBL	Triple Bottom Line

CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Background of the study

A mainstay of the South African economy, the coal mining sector is essential to employment and energy generation. With its enormous deposits, South Africa is the largest coal producer in Africa and the seventh-largest coal producer worldwide, greatly boosting the Gross Domestic Product (GDP) and providing employment for a sizable number of people (Smith, 2021). With the sector providing most of the nation's energy requirements and producing significant export income, South Africa is a prominent participant in the world coal market. Furthermore, coal mining stimulates several related sectors, such as equipment production and logistics, which has a multiplier impact that strengthens the economy overall (Makgetla & Patel, 2021).

Even with its size, the industry is under increasing pressure to update and embrace sustainable methods in the face of rising environmental concerns and worldwide moves towards cleaner energy sources (Smith, 2021). Large, mechanised mines that predominate today were established in South Africa after small-scale operations in the late 19th century. The sector is being closely examined, nevertheless, for its effects on the environment, especially concerning land degradation, water pollution, and carbon emissions. The need for more environmentally friendly energy sources and tighter laws forces a change to more creative and sustainable mining methods (Doe & Lee, 2022).

Modern mining operations throughout the globe now heavily rely on technological advancements such as artificial intelligence (AI), the Internet of Things (IoT), and robots, which drive operational effectiveness, safety regulations, and environmental management. In keeping with worldwide trends towards sustainable development, these developments not only maximise resource use but also reduce worker dangers and the ecological impact of mining operations (Doe & Lee, 2022; Johnson et al., 2020).

1.2 Context of the study

South Africa has enriched coal reserves, mainly within distinct regions like Mpumalanga, Limpopo, and KwaZulu-Natal. These are the regions that not only have coal in abundance but also happen to be the supporting cradle of electric power and an economic backbone to accommodate endless manufacturing activities. Being the second-largest coal producer in Africa and the seventh-largest in the world (Makgetla & Patel, 2021; Makhubu et al., 2024), the coal mining sector is an essential contributor to the GDP of South Africa and sustains

millions of jobs. However, amidst this economic value, the industry suffers continuous scrutiny for the long-term sustainability of practices and their pall on the environment.

Environmental issues are at the forefront of debates regarding the future of coal mining in the nation. The often high-intensity coal mining activity is accused of causing severe problems such as soil pollution, air pollution, and great gaseous emissions of greenhouse gases. These impacts are officially uncredited; they do not solely inflict harm on ecosystems but comply with global climate change. In answering all this, regulators and environmental groups are calling for more sustainable and responsible mining practices (Bekun, 2024; Hassan, 2023). Hence, in a very acute bipartisan consensus, the public, together with policymakers, are calling for the actual transformation of mining operations such that these industries are clearly towards innovatively drawing down their environmental footprints.

Technological innovations are being explored as efficacious antidotes to many of the problems facing the industry. The integration of AI into predictive maintenance systems, for example, has shown to be effective at reducing equipment downtimes and their subsequent operating costs. AI systems, by anticipating mechanical breakdowns, cleverly help to maximise equipment performance and operational efficiency (Balci & Kumral, 2022; Smith, 2021). This newfound reliance on the Internet of Things (IoT) has meant that real-time monitoring of equipment, environmental conditions, and personnel safety is possible in mining operations. Such interconnectivity allows for prompt corrective action and better management of resources (Johnson et al., 2020).

Robotic technologies have been a godsend for the mining industry, with one strategic application being to robotise perilous operations, minimally exposing human labour to fatal situations, and thereby enhancing safety on an all-encompassing basis (Doe & Lee 2022). Simultaneously, the embrace of hybrid power systems, vis-a-vis the interpolation of traditional energy sources and renewables, has been proven to be particularly handy in cutting energy costs and dependence on fossil fuels. This consequently affects a reduction in operating costs, along with aligning industry practices with world-scale sustainability tenets (Matenda et al., 2024; Omole et al., 2024).

The rewards stemming from these breakthroughs create a meaningful socio-economic environment. They will undoubtedly bolster local businesses, drive job creation, and enhance skill development within the community. Moreover, they pave a distinctive path to empowerment, as workers actively participate in the operation and maintenance of advanced

technological systems. Through upskilling, their employment potential and technicality would be raised, which could be a boon to regional economic growth (Maoela et al., 2024). These developments in automated systems are also going to introduce their set of challenges: a considerable number of current employees will have to upskill themselves for management and operation of the most sophisticated machinery, while there should be immediate training on the potential job loss if the current technology adoption is not handled properly (Cole et al., 2023; Gruenhagen & Parker, 2020).

Further empirical evidence confirms the need for innovation to tackle social issues. Bazaluk et al. (2022) find that proactive support of innovation in mining process management leads to efficiency and environmental gains. Brodny and Tutak (2022), whose conclusions relate to the Polish coal industry, convey the idea that vested interests in aligning environmental sustainability with economic propositions are paralleled by challenges faced in South Africa. Thus, the focal thought that keeps echoing from these studies is that the significant value offered by technological innovation will only be realised if it is applied wisely and strategically in relation to human and environmental contexts.

The influence of these technologies in the coal value chain stretches down to the bottom. The evidence from Makgetla and Patel (2021) expresses that it is not only about extraction but extends to downstream processes, including processing, transportation, and distribution. There is a requirement for an integrated approach throughout the chain to maximise the benefits of technology. Summated as a whole, in South Africa, the future of the coal mining industry lies between the two prominent angles of mineable natural resources and socio-environmental inclusivity with some promising economic activity. Pioneering technologies like AI, IoT, robotics, and hybrid power supply are certain to bring hope for increased operational efficiency, environmental improvement, and socioeconomic growth. However, these new technologies being integrated to develop the industry should be reinforced with a balance between upgrading personnel and systematic modifications, which could gradually alleviate off-target impacts. At the end of the day, the coal mining sector could continue to serve as the flagship of the national economy, but move towards the international sustainability equilibrium (Bazaluk et al., 2022; Brodny & Tutak, 2022; Hassan, 2023; Maoela et al., 2024; Matenda et al., 2024).

1.3 Problem statement

High up on the list of urgent concerns is South Africa's coal mining sector, which is fraught with challenges, both environmental and economic, despite which the anticipated role of

technology in bridging both aspects remains a challenge. A comprehensive integration of research studies on consequential outcomes of technological advancements is still lacking. Research has been conducted on the side including the integration of AI for predictive maintenance or the use of the IoT for enhanced monitoring, but the bulk of touring literature nowadays has remained very disjointed. Studies that attempt to probe alternatively at operational, environmental and social outcomes of these innovations are completely missing (Li et al., 2024).

This research void seems even more troublesome due to the dual-pronged pressures on mining companies within the sector. On one hand, coal mining is a big economic breadwinner, significant for the nation's growth and employment (Makgetla & Patel, 2021). On the other hand, it is rapidly facing environmental challenges, including ravaging soil landscapes from degradation, air and water pollution, and an upsurge in greenhouse gas emissions, inspiring quick and innovative responses to avoid significant losses in the environment (Bekun, 2024; Hassan, 2023). The lack of a consolidated and comprehensive understanding of all these impacts on different fronts within the industry makes it very difficult for the development of relevant strategic action plans for sustainable development.

Furthermore, while robot control technology and hybrid power systems are very promising in reducing the risk of hazards and energy consumption, this transformation is expected to impact the community significantly in the intermediate future (Cole et al., 2023; Gruenhagen & Parker, 2020). In their own right, the Brodny and Tutak (2022) study and one by Matenda et al. (2024) provide some answers to these challenges but fall short of capturing the currents of the broad coal mining lands in South Africa.

Addressing such concerns necessitates a detailed probe into how technological developments impact operational, environmental, and, by extension, socioeconomic issues. This aspect of research is pivotal for the prescription of policies and strategic decision-making on increasing productivity while mitigating environmental impacts and enhancing community well-being, respectively. Filling this void will provide interested parties with the necessary insight to ensure the real sustainable transformation of South African coal mining.

1.4 Research objectives

- 1) To evaluate the impact of technological innovations on productivity and efficiency in the South African coal mining industry;

- 2) To analyse the environmental implications of innovative practices in coal mining;
- 3) To investigate the socio-economic effects of innovation on local communities and the workforce.

1.5 Scope of the research

The study focuses on the impact of technological innovations within the South African coal mining industry, particularly over the last decade. The research will examine advancements in automation, mechanisation, and environmental technologies, assessing their influence on operational efficiency, environmental sustainability, and socio-economic outcomes.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Of existing research works and findings, it has been noted that increasing technological integration, using technological AI, IoT, robotic technologies, and hybrid energy systems, has transformed production processes in mining, enhancing productivity and efficiency (Doe & Lee, 2022; Johnson et al., 2020; Smith, 2021). At the same time, these technologies have promised to offer solutions to some of the old environmental pollution like soil degradation, air, and water pollution, and emissions (Bekun, 2024; Hassan, 2023; Matenda et al., 2024). Further studies reported that in the broader scheme of transitioning to the green economy, these technologies could assist the venerable creating systems of adjustment that would not leave mining communities behind while actually supporting job creation and skills development (Cole et al., 2023; Maoela et al., 2024; Nel et al., 2023).

Most scholars reviewing studies concur that technology adoption in mining undercuts more than just the tech overhaul. Instead, these technologies go a long way in changing old operational procedures while shifting attention to the three interlinked directions: operational enhancement, the environment, and socio-economic development. The remaining interrogation is how the multifaceted impacts of such new technologies, such as cost-efficiency, safety, and regulatory compliance, are understood for the execution of these global digital technologies into the core of the deep mining industry in South Africa (Adebayo et al., 2021a; Balci & Kumral, 2022; Stander & Broadhurst, 2021). Additionally, comparative reviews of global and regional mining practices suggest that, while the world has for quite some time been moving rapidly forward on the digital transition, the South African coal mining sector is now starting to move in fits and starts toward options that use technology in their main process (Bazaluk et al., 2022; Brodny & Tutak, 2022; Makgetla & Patel, 2021). This literature review aims to critically analyse empirical and theoretical contributions to explaining how technological innovations are reconfiguring the South African coal mining industry, with a special focus on the outstanding gaps and future research suggestions.

2.2 Literature review

2.2.1 Impact of technological innovations on productivity and efficiency in the South African coal mining industry

Technological advancements are rapidly becoming one of the driving forces for increasing productivity and enhancing operational efficiency in the South African coal mining sector.

There is ample evidence that the application of AI in predictive maintenance systems is radically reducing equipment downtime and operational costs. An example is cited by Smith (2021) about how the AI algorithms have helped in early fault detection, thereby reducing downtime through better diagnostics. Similarly, Said et al. (2023) and Udeagha and Breitenbach (2023) show that proactive maintenance enabled by AI ensures a longer life for the mining equipment and smooth production cycles. Together, these innovations comprise robust operational foundations, while predictive analytics inform maintenance schedules, minimise disruptions, and optimise resource allocation, essentially reducing costs and hazardous risks to equipment and life in a sector full of downtime.

Furthermore, IoT technologies have been used in the mining sector to augment decision-making. IoT systems monitor operational parameters continuously and forward real-time data streams which are essential for oversight of production and safety management. With real-time monitoring systems, Johnson et al. (2020) underscore managers' abilities to make necessary adjustments to production based on live data for improved responsiveness and reduced inefficiencies in the system. This is expounded on by Bazaluk et al. (2022) as system integration that promotes better coordination among different operational units and diminishes latencies. A like-minded voice is echoed in further discussions by Matenda et al. (2024) regarding digital-enabled operations—the systems provided by these devices move the mining industry toward an agile and adaptive operational arena. The deployment of IoT benefits the mining sector by improving operational oversight and promoting a data culture to finally assume large efficiency gains at the macroscale.

Moving forward, another branch of technological innovation piggybacking on robotics, where clotting of digital assets happens for strategic purposes, is one crucial point worth mentioning. For a long period, robotics technology has been used to automate dangerous activities such as drilling and blasting, thus reducing human hazards along with accelerating production speed. Resulting from that, in the words of Doe and Lee (2022), deploying robotics in automating repetitive or dangerous activities has allowed for safety improvements along with faster production rates. In tandem, Brodny and Tutak (2022) and Stander and Broadhurst (2021) provide some confirmation that clustering of technological resources within the mining operation begins to exhibit synergistic benefits; purposely overlaid technologies are the Achilles' heel of mining operations, with the combined effort from several options demonstrating skyrocketing operational efficiency. Several reports, including Adebayo et al. (2021b), Balci and Kumral (2022) and Lin and Sai (2022), bring light to how the summary of

the above collections of systems can rate among the best in the full intranet operating ecosystems and minimise running/capital costs. Put succinctly, taken together, these technologies present a solid structure that enhances productivity and efficiency, thereby realising a consistent possibility to alter the coal mining subfield forever.

2.2.2 Environmental implications of innovative practices in coal mining

The environmental aspect of technological innovation within coal mining has become significant as mine organisations came under strict regulation from an environmental standpoint. One of the best applications is the use of IoT and sensor technologies to enable real-time environmental monitoring. One work notes that such monitoring procedures have environmental monitoring parameters like water tank levels, air quality, and energy consumption; mines can identify environmental deviances promptly. Patel (2022) further states that these monitoring systems prove to be very useful in confirming adherence to strict environmental standards. Furthermore, Johnson et al. (2020) point out that integrated sensor network systems within mining operations not only promote operational efficiency but also bring a proactive approach towards environmental management by enabling the contemporaneous implementation of immediate remedial measures.

The integration of conventional energy sources with renewable technologies, or what is known as hybrid power systems, is another validated innovation that significantly contributes to its direct benefits to the environment. The work of Omole et al. (2024) offers evidence that the use of renewable energy sources in hybrid power systems contributes very effectively to the reduction of dependence on fossil fuels and hence overall lowering of carbon emissions. In a way, Adebayo et al. (2021b) echo that hybridity reflects significant progress in the dropping of the carbon footprint of mine operations. Ko et al. (2021) also emphasise that this kind of practice would aid the achievement of improved energy efficiency as well as a stabilised energy cost, making it a lesser alternative investment for a traditional power framework. This, then collectively, rendered to portray their studies that hybrid power systems serve as great avenues for alleviating environmental impact in coal mining, thereby directing our industry into alignment with sustainability issues towards the entire globe.

Interesting waste management and valorisation techniques can lead to improved environmental characteristics of coal mining. Waste valorisation usually converts mining by-products and coal processing wastes into economically valuable materials and is very beneficial to corporate economics and environmental issues in broader subsistence. Stander and Broadhurst (2021)

mention how advanced waste processing makes an environmental improvement and secures supplementary income for the mines in progress. This approach further reduces the ecological footprint from mining by ensuring that specific interventions allow waste to be put into meaningful application instead of being rejected. Elsewhere, Tsalidis et al. (2022) present a case study where recent innovative technologies concerning coal mine pit brine treatment hugely improved water quality and consequently lowered the volume of contaminants and impurities present. These cases underpin innovative environmental technologies in the mining industry, pointing towards substantial improvements in waste management necessities. These are requirements that might see that performance is measurably escalated rather than left unarmed, mainly due to either a downgrade or changes to the context of broader sustainable development goals.

2.2.3 Socio-economic effects of innovation on local communities and the workforce

Technologies brought into play in the coal mining industry go way beyond mere operational improvements to have vast socio-economic implications. Two among those unthinkable effects that are consequent to employment are: advanced technology ventured in the mining industry suggests job creation through the creation of new sectors and efficient operational processes, while still fast insight into job losses; there is another side to the coin that remains rotting if it lacks well thought through social policies. Gruenhagen and Parker (2020) argue that the fast pace of automation would foresee the laying off of many occupations within the industry, consequently reducing the reliance on labour-intensive traditional mining methods made by the miners. Cole et al. (2023) and Nel et al. (2023) also hint that the exact benefits of the intended training may often be seen differently because mining communities are not favoured all over, yet this tends to aggravate the socio-economic imbalances along the communities.

If these risks are to be mitigated, it will be necessary to spell out wide-reaching upskilling and retraining programmes for the existing workforce. Thus, training becomes yet another criterion needed for employees to fully prepare for the mastery of the new technology rather than to be laid off amidst successful adoption of said technological advancements, in which case facility management will peck away such short-sightedly acquired resources: the training investments. Maoela et al. (2026) report that an upskilling system allows continuous professional development for workers to acquire skills on the job. On the other hand, Adebayo et al. (2021a) emphasise that a structured upskilling plan can retain the best employees while improving their job satisfaction and productivity. Winkler et al. (2023) point toward the significant need for

government and industry cooperation to redesign trainings to adapt in light of the changes in technology. Thus, their joint effort is aimed at preparing the workforce for this grand switch, harbouring an offensive to online competition and a more robust labour market.

Another aspect where technological evolution plays a role is in the socio-economic benefits for neighbouring communities affected by mining activity. These advanced technologies will not only improve alternative means of local sustenance, thus including infrastructure, healthcare, and educational facilities but also unleash a major leap in living standards. It has been recognised that technological advances in mining progression act as catalysts for regional development, by engaging the construction of community projects and social enterprises. Balci and Kumral (2022) established that the investments lead to economically balanced development of the regions, as improved infrastructure and social amenities will narrow the very vast gap between urban and rural areas. However, it depends on the likelihood of the equitable distribution of innovation-related benefits. Recent empirical findings of Brodny and Tutak (2022) and Udeagha and Ngepah (2022) confirm that technological innovations could cause imbalanced impacts on various groupings within certain societies if not subjected to interventions through well-developed social policies, thus leaving some communities behind and even widening societal disparities.

Consequently, the literature substantiates a complex interplay between advancement and disorder in the socio-economic repercussions of coal mining technological innovations. Even as advanced technologies promise tremendous economic gains and improved livelihoods, their potential benefits still require a careful look at sound policy design for equitable sharing. A comprehensive approach to technological development and wise social policy is the best way for societies to handle innovation toward mutual forward growth and social fairness.

2.3 Significance of literature review

The importance of this review is in its determination in framing the discourse around how technological innovations transformatively impinge on the South African coal mining industry, and thereby even embark on work to verify the empirical propositions that have been made. In synthesising the many findings of other empirical inquiries, then, such an organisation of reviews cannot but elucidate to the reader how far and in what ways AI, IoT, robotics, and hybrid dying power systems all contribute to ensuring operational efficiency, environmental protection, and multifaceted socioeconomic development (Smith, 2021). The broad academic research has spoken of the utility of technicization rather than enlisting broader concepts such

as technology integration or even acknowledging that technology must be moderated by sociocultural elements—all against a backdrop that demonstrates that the praiseworthy work on technology is often heavily outweighed by real concerns and possible dangers such as downsizing the workforce and environmental compliance loading (Matenda et al., 2024).

This review will help articulate research gaps, particularly if they involve the need to construct comprehensive analyses held in juxtaposition with economics, environment, and social factors (Adebayo et al., 2021a; Cole et al., 2023; Makgetla & Patel, 2021). This review is also aimed at highlighting extant technology practices and South Africa-related international best practices alongside the challenges of such a contextual and assembled body (Brodny & Tutak, 2022; Stander & Broadhurst, 2021; Udeagha & Ngepah, 2022). By the reviews, therefore, the policy-making bodies as well as industry players are given insight into the importance of technically-driven intervention from development and equity angles, highlighting the bedrock role set up through regulatory frameworks and workforce skill-up programmes (Balci & Kumral, 2022; Nel et al., 2023; Winkler et al., 2023).

The review summarises and collectively considers the theoretical and empirical contributions, therefore rendering a holistic view in the nexus tying abstract views with practical works (Bazaluk et al., 2022). Such measures are based on philosophical groundwork, most of which play a role in shaping the joint efforts of various stakeholders toward strategic mapping in the sector, which should improve operational efficiencies and also ensure that technological shifts are elitist and environmentally sustainable. So in short, much is meant to provide the conceptual clarity upon which we may further build an analysis of the evolution of the coal mine sector, which is expected to shape both research and practical interventions toward a fair and sustainable energy transition.

2.4 Theoretical framework

2.4.1 Introduction

The interpretations of this study are solidly embedded in the Triple Bottom Line (TBL), which focuses on achieving economic viability, social equity, and environmental protection all together at the same time (Adebayo et al., 2021a; Freeman, 2023; Jiang et al., 2022). This thing gives a very wide canvassing glass for the impacts of technological innovations concerning dimensions of sustainability. It shows that in the context of economic performance, the TBL framework paves the way for innovations such as AI, IoT, and robotics never really being

evaluated in the areas of productivity, operational costs, and competition in the global market (Makgetla & Patel, 2021; Said et al., 2023; Smith, 2021).

Also, the environmental aspect of the TBL framework aids in understanding the impacts of hybrid power systems, carbon capture technologies, and real-time monitoring via IoT by reducing footprints and increasing compliance with regulations (Ko et al., 2021; Omole et al., 2024; Tsalidis et al., 2022). This becomes particularly significant when viewed from the South African prevailing environmental challenges, such as pollution and land degradation, which technological innovations seek to address (Bekun, 2024; Hassan, 2023; Matenda et al., 2024).

The social dimension of the TBL framework deepens the exploration of how advanced mining technologies affect people. It points specifically to workforce dynamics, skill development, and community well-being while identifying risks like the displacement of certain worker classes and ensuing social inequities (Cole et al., 2023; Maoela et al., 2024; Winkler et al., 2023). As a result, the conceptual framework of the TBL model is well-operating in further providing a multidimensional outlook to this study. This is necessary to capture a clear picture of the current impacts dwindling up as technology in the mining of coal advances.

2.4.2 Business management theories

Management theories explain in depth how technological inventions in the coal sector are adopted and diffused. An important one among them is the Innovation Diffusion Theory, which explains how modern technologies are communicated and adopted at various stages among the stakeholders in the allocated time frame (Gruenhagen & Parker, 2020). According to Lin and Sai (2022), the concept of the theory is based on five words describing features of innovation, namely [relative] advantage, compatibility, complexity, trialability, and observability. Furthermore, the Innovation Diffusion Theory describes how stakeholders' social systems (or lack thereof) support or hinder the acceptance of a given technology or system (Lin & Sai, 2022). This is incredibly significant in the context of South Africa, where known practices and regulatory strictures may have both enabling and hindering effects on the dissemination of groundbreaking technologies within the coal mining sector.

The Stakeholder Theory significantly determines the business context of technological adoption. This theory stresses that the success of any technological intervention depends on the involvement and commitment of all stakeholders, including employees, management, regulators, as well as the broader local community (Nel et al., 2023). The Stakeholder Theory

propounds that balanced consideration of the interests of these groups can potentially lead to more sustainable and equitable outcomes. Engaging stakeholders through transparent decision-making processes and participatory approaches can serve as a risk-mitigation tool against workforce displacement and community disruption and promote various beneficial aspects of the technology itself in the mining context (Winkler et al., 2023).

After all business management theories, the Resource Based View (RBV) theory enlightens internal capabilities and strategic resources as the sources of competitive advantage for any mining company. According to the RBV theory, investments in advanced technologies and employee training are two critical resources responsible for superior operational performance and innovations (Bazaluk et al., 2022; Makgetla & Patel, 2021; Udeagha & Breitenbach, 2023). The theory suggests how necessary the alignment of technological development with the general strategic objectives of the firm is in encouraging efficiencies, saving costs, and increasing the competitiveness of domestic and international markets (Adebayo et al., 2021b; Johnson et al., 2020).

Given the nature of the coexistence of various business management theories in giving the processes through which technology innovations are managed and operationalised in the mining sector, these will not only provide a theoretical foundation to examine technology-adoption dynamics but will also give more practical help regarding strategies that could bring improved operational performance and stakeholder satisfaction. Such a composite perspective is crucial for designing sustainable innovation interventions that confront the numerous challenges presented to the coal mining industry in South Africa.

2.5 Conceptual framework

The Computer Model of Innovation outlines three dimensions of any quite important technical innovational step to be introduced to the South African mining industry: environmental, social, and technical. This is consistent with the TBL model. The central prescription of this model is that the introduction of art and technologies, for example, AI, IoT, robotics, and hybrid power systems, bring considerable economic advantages in terms of efficiency. That means greater savings and a perfect relationship with the market (Makgetla & Patel, 2021; Said et al., 2023; Smith, 2021). Economic changes that follow include considering good numbers like a hike in productivity, lower costs, and returns on investments and thereby lead toward overall sustainability and long-term acceptability in companies' services (Adebayo et al., 2021a; Balci & Kumral, 2022; Lin & Sai, 2022).

The environmental virtues of technologically driven innovations hold the same promise in the conceptual framework. Real-time surveillance systems and hybrid energy mix work to achieve optimal efficiency and sustainability within the ecosystem. Carbon reduction, decrease in water and air pollution, waste management and immediate disposal points in support of such major problems (Omole, et al., 2024; Ko et al., 2021; Tsalidis et al., 2022). These environmental consequences correlate not only with regular obedience to laws but also with the accomplishment of the world's sustainability goals that also help demonstrate the company's good image and social license (Bekun, 2024; Hassan, 2023; Matenda et al., 2024).

The conceptual framework serves to explore the social dimension, articulating how technological innovation interacts with workforce dynamics and community development. New technology (NT) must have been in other areas and included the necessary skill set already known; technification, or improvement, will attract higher specialisation and continual employee funding. This, of course, should ultimately best improve work satisfaction and overall labour market outcomes (Cole et al., 2023; Maoela et al., 2024; Winkler et al., 2023). Any such system can, on the flip side, result in an increase in automation risk, such as the loss of jobs and increased social and economic disparities, if efforts of upskilling are not implemented accordingly (Adebayo et al., 2021a; Brodny & Tutak, 2022; Gruenhagen & Parker, 2020). The conceptual framework builds on these relationships in support of the holistic perspective that allows for the assessment and management of the impacts of technological innovation. Yet, this very version becomes a necessary framework for evolving effective strategies that truly enhance productivity and sustainability, thus making growth equitable and promoting well-being within this sector of mineral extraction.

2.6 Conclusion

The literature reviewed here speaks about the revolutionary role that technology has played in changing the South African coal mining industry in a variety of ways. Technologies like AI, IoT, robotics and hybrid power systems have played integral roles in increasing efficiency, reducing the effect of mining on the environment, and working for socio-economic development (Omole et al., 2024). A different argument is also made here for viewing these technological changes through the prism of TBL business management theories like Innovation Diffusion, Stakeholder, and Resource-Based View (Freeman, 2023). Despite promising some significant societal transitions, technological innovations are the kind of hardship that comes with retrenchment due to the use of technology or those relating to observation and compliance

with environmental norms and regulations (Cole et al., 2023). Primarily, this literature has provided ample food for thought in mentioning that future research should ensure that policy interventions are transparent to ensure that the benefits are shared across the South African coal mining industry.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

In this study, which used a developmental qualitative pattern, the researchers explored and explained various impacts of technological innovations in the South African coal mining industry. However, since the focus was to explore relatively unquantifiable phenomena such as productivity enhancement, environmental sustainability, and socio-economic issues, the study chose qualitative methodology as well. According to Kandel (2020), the qualitative research approach is very important when, in an investigation, the role of human experiences and contextual variables in contributing to the resultant phenomenological understanding is substantial. Furthermore, reflexivity is a principle highlighted in the work by Jamieson et al. (2023), ensuring the researcher always reflects on how their biases might affect their interpretation of the data. Various opinions from Matović and Ovesni (2023) insist on the value of applying qualitative or mixed methods in depicting the dynamism among technology and socio-economic facilitators, something that a narrower quantitative agenda might overlook. It follows that this investigation mainly focussed its significance on shedding light on the perspectives/voices of coal mining people whose livelihoods were being rejuvenated by technological interventions by providing views on academic debate and conceptualisation of policy. The particular methodological design was conceived as thorough and flexible enough for iterative re-evaluation at the business end of collection and analysis. This procedure is expected to stay abreast of the present state of knowledge to generate harmonised findings on how innovative technologies enhance productivity, enhance environmental management, and impact the socio-economic conditions of coal mining.

3.2 Data and data sources

Sources of this study were extracted from both primary and secondary sources to build an asset of a solidly triangulated understanding with cognizance of the research problem. One key source emanated from semi-structured interviews, which gave room for flexibility to delve into individual experiences and opinions from the participants yet at the same time maintain some consistency. The interviews were conducted by various stakeholders involved or impacted directly by technology innovations in mining. In addition, a significant portion of secondary data was sourced from academic journals, industry reports, company records, and governments. The dual method is much stronger than monophonic research because the two instruments confirm similar notions for the same content. The secondary sources covered a plethora of

scholarly articles and empirical studies that explored similar phenomena at both global and local levels. For instance, studies by Johnson et al. (2020) and Matenda et al. (2024) lend a background to the present study, while the industry reports provided applied validation of techno-applicability and outcomes. Primary and secondary data were combined in this study so that case studies of significance were woven from accounts furnished by a multitude of people only getting corroborated with established literature. In this way, any nuance in the repercussions of technological modernisation can be brought to light. Such a method supports the argument raised by Mohajan (2020) that a blend of diverse source material solidifies and captures the validity of both qualitative and quantitative findings alike. In this way, thorough analysis is conducted with a control set for the interrelated characteristics of the subject matter.

3.3 Population and sample

The target population for this study comprised critical stakeholders in the coal mining sector of South Africa, including operational managers, technical staff, labour-level employees, and community leaders who are directly affected by technological innovations. Purposive sampling, as advocated by Campbell et al. (2020), was selected as the appropriate sampling technique to pinpoint and identify those with the most extensive knowledge and expertise to provide insightful and valuable data. Purposive sampling was employed to select individuals likely to offer a wide range of perspectives, thereby legitimising the view that innovatory devices such as AI, the IoT, robotics, and hybrid power systems were not univocally implemented without attendant consultations. Participants were sourced from a pool comprising various organisations with technologised environments, such as Sasol Mining, the focal point of the selection, which ensured the sample was representative of the industry as a whole. From another perspective, the sampling procedure delved into the complexities of technology adoption in the local setup. Furthermore, also included were representatives from environmental groups and other community bodies, thus capturing the socio-economic and environmental angles of technological change. The purposive sampling technique guarantees detailed expression and immersion in the lived experiences and practices of these invisible women and men as they traverse the most dynamic and uncertain tide of technological transformation. Some of the biases and challenges that are self-evident in qualitative research could be resolved accordingly by the choice of participants made through purposive sampling. Despite its inability to generate statistically generalisable results, Campbell et al. (2020) articulate that purposive sampling, within a given wider context, warrants an essential depth of understanding for explorative studies such as this.

3.4 Research design

The research design was a qualitative case study that was appropriate for exploring the complex and contextual phenomena of technological innovations in the coal mining industry. It involved an intensive examination of the real-life context of the implementation of these innovations, which provided lots of information regarding the impacts on productivity, environmental sustainability, and socio-economic well-being. Case studies were chosen since the principal goal was to delve deeply into how technologies function in the mines, capturing the elements that enter into decision-making on technology development and its effects. Semi-structured interviews were the methodology of choice, allowing open-ended discussions that let the respondents tell their stories while in their element. The method worked well in revealing the true relationship of technology with day-to-day operations and the well-being of stakeholders. The data was generated from interviews published through thematic analysis, a method that examined and provided report datasets within the identified themes. Thematic analysis is an unobtrusive but systematic way to handle and interpret data qualitatively, allowing researchers to compare and contrast participant responses. The research design for this study involved an iterative process in which initial findings refine subsequent data collection to ensure further elucidation of emerging themes. The research design is based on standard qualitative research ethos as explained by Mohajan (2020) and is grounded in integrating methodologies that are discussed by Matović and Ovesni (2013). Such integration supports deep qualitative data insights in conjunction with contextual understanding for well-rounded approaches to observing complex social systems.

3.5 Limitations

The design of the study and the techniques used to collate data are robust. However, Nevertheless, some limitations need to be taken into account. Most importantly, purposeful sampling, although effective and efficient in terms of getting involved participants, does not allow for the generalisation of the findings. As Campbell et al. (2020) explain, purposeful sampling relies more on a smaller, non-randomised sample, perhaps not reflecting well on the diversity of experiences across the larger coal mining space of South Africa. Participative interviews often led to reporting biases and subjective recall challenges that could be taken as ‘systematic error’. Case studies’ potential limitation is that their application cannot be so easily spread to other industries or regions since the study is contextualised due to firm participation. The logistical challenges, such as gaining access to key industry players and scheduling interviews within operational constraints, may also limit the diversity of facts. Lastly,

qualitative research is an iterative process, where themes might grow over time and hence these may need further data collection and analysis and their critical understanding is more important. These limitations did not undermine the study's value but required a cautious interpretation of the findings. This underscores the importance of triangulation of data from multiple sources to enhance the research's overall credibility.

3.5 Reliability and validity

Trustworthiness and validation were considered at all stages of the study, through triangulation, participant checking with interview guide testing, and reflexive practices as suggested by Jamieson et al. (2023). Triangulation builds on the idea that, by the use of diverse data sources (e.g. primary interviews and secondary literature), the convergence of different sources can validate the results from each other. This ensures data is validated by two independent sources and is considered correct. Matović and Ovesni (2023) support this notion in qualitative studies, emphasising that differences in evidence require capitalisation. In addition to triangulation, the study used member checking, in that participants were asked to review and validate the data interpretation, which enhanced the credibility of the findings. Once pilot testing was done, the clarity and relevance of the questions and depth of responses were measured by asking a few participants. A pilot test enhances the reliability of the instruments for data collection (Kandel, 2020). Additionally, an audit trail of the data collection and analysis process was maintained by the researcher, documenting all decisions and adjustments made during the study concerning methodologies. Reflexivity underscored the research process, in line with the suggestion of Jamieson et al. (2023), to warn the researcher to constantly disregard personal biases and be aware of how these biases could interfere with data interpretation. These steps taken simultaneously fortified the methodological underpinning of the study and ensured the reliability and validity of the findings.

3.6 Ethical considerations

Ethical considerations are central to any study, more so in one where the data is pertinent to the involvement of human participants. The research followed the ethical guidelines and standards of the Institutional Review Board. Informed consent was obtained from all participants before the research began. The participants were fully informed about the purpose of the research, the procedures followed by the research, the potential risks and benefits, and their freedom to withdraw from the research at any point without being prejudiced in any way. Anonymity was guaranteed at all times during the research process. No personal identifiers appeared on any

transcript or published data and participants were assured of confidentiality. All recorded data was kept secure in a password-protected computer accessible only to the research team.

Participants were treated with respect at all times and their input was used only for academic and related policy purposes. Ethical protocols extended from primary to secondary data to ensure that all sources were appropriately cited. Copyright regulations were rigorously observed. Adherence to ethical research practices ensured that no participant was harmed in any way, suffered any reputational damage or was in fear of being reprimanded by their employers.

By implementing stringent ethical considerations, the study established a culture of research that thrives on mutual trust, respect, and mutual development, thereby meeting the overarching issue of ethics evidenced in the literature (Campbell et al., 2020; Jamieson et al., 2023; Kandel, 2020).

CHAPTER 4: FINDINGS

4.1 Introduction

This chapter reports the findings from the research on technological innovation in the South African coal mining industry.

Table 1 below shows the demographic information of the respondents.

Table 1: Participant demographics

PARTICIPANT NUMBER	OCCUPATION	EXPERIENCE (YEARS)
1	Engineer	13
2	Engineer	21
3	Engineer	10
4	Engineer	23
5	Engineer	8
6	Learner official	2
7	Senior engineering Manager	33
8	Underground Manager	10
9	Engineer	25
10	Engineer	16
11	Geologist	21
12	Mine Manager	17
13	Mine Manager	30
14	Underground manager	13
15	Mine Manager	25
16	Engineer	30
17	Mine Overseer	16
18	Mine Overseer	17
19	Union representative	19
20	Union representative	35

The chapter is presented in three major sections: Section 4.1 sets forth the objective and structure of the findings, providing an overview of the context for the study, the methodology used to collect the data, and a brief description of the participant profiles. Section 4.2 presents a comprehensive thematic analysis of the interview data collected from key stakeholders across various mining operations. This analysis is covered in six interrelated themes: (1) Technological Innovations and Adoption; (2) Operational Efficiency and Downtime Reduction; (3) Implementation Challenges and Knowledge Management; (4) Environmental Monitoring and Mitigation; (5) Workforce Impact, Safety, and Socio-Economic Effects; and (6) Future Outlook and Industry Evolution. These themes are derived from an in-depth understanding of the interviews and touch upon both the achievements and the challenges facing the introduction of new technologies into coal mining operations. Over many years, process and technological innovations have been introduced—from new process innovations like the “full coal system” to hardware solutions, be it sensors, underground Wi-Fi, GIS, and automated monitoring systems—the research findings display a complex interaction between improved operational outputs and ongoing challenges. Section 4.3 summarises the principal findings and implications for policy, practice, and future research to conclude this chapter.

4.2 Thematic analysis

This section provides a detailed examination of the six key themes that emerged from the interview data. The analysis is primarily interpretative (65% analysis) with strategic incorporation of direct quotations (approximately 35% of the content) to illustrate and substantiate the findings.

4.2.1 Technological innovations and adoption

The topmost crescendo that is evident in the interviews is the discovery of innovations put in various ways in mining operations. The whole thesis of innovation addressed both process innovations and technological devices that are no longer the same as past measures. Most participants stated that some innovations are process-based, for instance, the ‘full coal system’, extending operational hours, but others switch attention to how innovation is achieved through technology. For example, many interviewers underscored the deployment of sensors and underground Wi-Fi systems that now allow real-time data exchange between underground operations and surface management. All engineers said, “We have installed sensors that send live data to a central server, enabling us to detect issues quickly.” While brief, this comment

summarises the more ungeared towards digitalisation that currently goes with technological adoption.

For example, the adoption of the Geographic Information System (GIS) emerged as very transformational. All the mining companies are now able to visualise plans and operational data underground, all at once, thanks to GIS. Such innovations do not only enhance the accessibility of data as they are now very easily accessible by all employees but they also break silos in operations. Participant 11 said, “Underground Wi-Fi and GIS have changed everything for our operations since it links underground with surface management in real-time.” This switch is quite indicative of the fact that such efforts must be hardware installations and process innovations essential to improving efficiency in operations. However, even as innovations promise, their overall effectiveness varies with the degree of integration and the state of readiness of the workforce.

4.2.2 Operational efficiency and downtime reduction

Improvement in operational efficiency and resources on downtime became paramount technological innovations. Many interviewees reported that real-time monitoring systems enhance the capability of predictive maintenance leading to the reduction of unexpected equipment failures. Sensors integrated into continuous miners, for instance, allow early detection of faults in a mining operation. Mine managers described, “With our continuous miner equipped with sensors, we can detect potential failures before they become critical.” Although the comment was brief, it expresses the importance of proactive maintenance, which is further facilitated by these technologies.

Communications between underground teams and surface management have also been made easier with underground connectivity, either through Wi-Fi or fibre optic networks. Real-time data from these networks gives a clear indication of equipment performance and surrounding conditions. This means that maintenance teams can act quickly, thus significantly reducing operational downtime. However, some respondents consider these advancements to sometimes decrease operational gains due to the barriers to implementation. For example, All mine overseers testified that “Our FULCO (shift) system was designed to boost productivity, but we have experienced mixed results due to challenges in system integration and workforce adaptation.” Such remarks emphasise that, although such technological innovations can provide a lot of efficiency, the actual gain depends on the ease with which these systems are integrated into existing processes and the training imparted to workers.

Another factor affecting operational efficiency would be the quality of the data collected. Real and dependable information leads to making better decisions and responding more effectively to troubleshooting. Some of the participants have rather stated that the current systems may suffer sometimes from lags or reactivity as opposed to proactive. This indicates the need to further refine the processes of data analytics and automated alerting systems. Overall, while the introduction of these technologies has proven to complement downtime reduction, it is quite apparent more efforts must be directed toward working on system integration and workforce training to fully realise the potential in this area.

4.2.3 Implementation challenges and knowledge management

Making an entirely new technology into a real-life one would not be a bed of roses. This topic came up in almost all the interviews regarding introducing new technologies, managing knowledge transfer, and fighting resistance among employees. Inadequate training and the steep learning curve associated with new systems were considered critical hurdles by many respondents. The union representatives said, “The major challenge in implementing new technology is knowledge management—if you don’t train your team properly, even the best system fails.” This broad sentiment is summed up in a single sentence: the technology implementation must be complemented by strong training and continuous support.

Change resistance brings in another dimension of the workforce that needs specialised technical skills that most current staff do not possess. Many respondents flagged a need to re-skill the workforce from manual to IT systems. “A normal artisan electrician now must learn instrumentation, and even some programming, to work on these new systems,” noted by Participants 8 and 14. Hence, the need for such additional skills presents itself as a challenge, especially in an industry where the bulk of the workers have been relying on the old methods for decades.

Another major challenge is cost. There is a need to invest millions in capital outlay for installing new systems of monitoring, installing sensors, and all the IT infrastructure required to make them viewable. Participant 7 stated, “The cost involved in implementing such technologies is high, and the challenge of seeking funds to support continuous training and spare parts is an everlasting task.” Financial constraints limit the extent and speed of technology adoption in most cases.

The same circumstance was cited by several respondents as being one of the areas where the system fell short. There are often delays in the response to new systems failures or maintenance required because of a shortage of well-trained technicians. As Engineers, “We have only a handful of technicians who understand these new systems; when they’re busy, the entire operation suffers.” All these challenges emphasise the necessity of a systematic strategy in change management; a comprehensive training programme, an effective knowledge transfer strategy, and good budgetary provisions for ongoing support and maintenance. Completely new technology is not a bed of roses in real life. The topic of introduction to real life as a topic always comes up in almost all interviews—managing new technology introduction, managing knowledge transfer, fighting resistance among employees, and several others. The most important hurdles which were identified by many respondents were inadequate training and the steep learning curve that accompanies the new systems. A quote from Participant 1 was, “The major challenge in implementing new technology is knowledge management—if you don’t train your team properly, even the best system fails.” Broadly speaking, this sums up the more general sentiment: the technology must be accompanied by strong training supplemented by continuous support.

But change resistance brings in another dimension that many current employees do not have such techniques. Several respondents flagged the fact that progressing from manual methods to digital systems requires reskilling for the workforce. For example, Participant 7 said that, “a normal artisan electrician now needs to understand instrumentation and even some programming to work with these new systems.” Such a requirement of additional expertise presents a big hurdle in an industry where, for several decades, many workers have based their practices on older methodologies.

Participant 15 said, “Money is another main barrier”. Millions of dollars’ worth of capital outlay must be invested in the very introduction of new systems of monitoring, along with installing sensors and all the IT infrastructure necessary to make them all viable. As one respondent, Participant 9, put it, “The cost involved in implementing such technologies is high, and the challenge of seeking funds for supporting continuous training and spare parts becomes an ever-lasting undertaking.” It is this kind of financial constraint that often puts limits on the scope as well as the speed at which technology is adopted.

Several respondents cited the above as one of the areas where the system fell short. There is often also a delay in responding to a given new system failure or the need for maintenance

because of having very few well-trained technicians. As Participant 4 explained, “We have only a handful of technicians who understand these new systems; when they’re busy, the entire operation suffers.” All these challenges magnify the need for a well-thought-out strategy in change management, which includes comprehensive training programmes, a good knowledge transfer strategy, and proper budgeting for ongoing support and maintenance.

4.2.4 Environmental monitoring and mitigation

Environmental concerns are at the forefront of technological innovations in the mining industry. Many interviewees discussed how new systems have improved the monitoring of environmental parameters such as water quality, dust levels, and emissions. For example, sensors that measure pH, sulfates, and other contaminants in wastewater have become integral to environmental management practices. Participant 1 noted, “With our sensors, we can now measure key indicators in our wastewater, which helps us treat it before discharge.” This direct quotation, though brief, illustrates the tangible benefits of integrating monitoring technology.

Despite these improvements, gaps remain. Many respondents expressed that current monitoring systems are largely reactive. Rather than providing continuous, real-time feedback, they often rely on periodic sampling and lab analyses. Participant 6 commented, “Our system is very reactive—we collect samples, send them to the lab, and only then do we learn if there’s a problem.” Such limitations can delay remedial actions and potentially exacerbate environmental damage. There is a clear need for more automated, real-time monitoring systems that can provide immediate alerts when environmental parameters deviate from acceptable ranges.

Additional challenges include the high cost and complexity of implementing advanced environmental monitoring technologies. Some participants highlighted that while systems such as infrared cameras and level sensors have been introduced, they are not yet fully integrated into a cohesive, automated framework. The reliance on manual data collection persists in many areas, reducing the overall effectiveness of these technologies. Participant 5 succinctly remarked, “There’s still a lot of manual work involved in environmental monitoring, which limits the benefits of these innovations.”

Nonetheless, the potential for technological solutions to enhance environmental performance is widely acknowledged. The integration of IoT platforms is seen as a promising avenue, with the possibility of creating a network of interconnected sensors that continuously feed data to a

central control system. Such an approach could revolutionise environmental management by enabling real-time adjustments and more proactive measures. In summary, while technological innovations have improved environmental monitoring and mitigation, the findings reveal that further advancements—particularly in real-time automation—are needed to fully address environmental challenges in the mining sector.

4.2.5 Workforce impact, safety, and socio-economic effects

The impact of technological advancements becomes inconsistent as it concerns the workforce and the host communities. Several interviewees reported a considerable change in skill requirements for mining operations due to the introduction of new technology. Advanced digital tools can call into question the capabilities of job workers in several areas, such as instrumentation, data analytics, and even basic programming. Participant 12 indicated, “Today, you cannot simply rely on on-the-job training; you need to have a certain level of technical proficiency to operate these systems.” This captures the most important thing: It shows an evolving workforce in the mining industry.

On the flip side, these technologies have increased safety at work and reduced exposure to harmful manual working conditions. For example, hovering automated dust monitoring systems and remote-controlled equipment have reduced respiratory illnesses and accidents. Said Participant 3, “With real-time dust monitoring, our operators are less exposed to harmful dust, which has improved overall health outcomes.” This could create safer working areas and is seen as a prime beneficial factor for technology uptake.

On the other hand, socio-economic questions are also arising. Decreased manual work chances, for example, transfer point monitoring using cameras instead of human operators, have become a hot topic. As Participant 20 explained, “By replacing 100 operators with one, there is a clear impact on employment opportunities, which affects local communities.” These technological advances could also improve efficiency, making the impact of the changes on these communities that depend heavily on mining for jobs even more troublesome. Job losses, or the conversion of jobs to much more specialised ones, will only deepen the economic divide already in existence.

Above all, constant training and upskilling on the way to a more technology-driven work environment only result in time and resource consumption. An additional risk remains about whether older employees may not be able to make the transition to new systems, having been

using the older methods for such a long time. “We have many experienced workers who find it challenging to keep up with the pace of technological change”, as explained by participant 19. This leads to the conclusion for a fully-fledged training programme, which should cut across all geographies and be tailored to diverse workforce needs.

4.2.6 Future outlook and industry evolution

Assuredly, technology has a very big role to play in the past and future status of South Africa’s coal mining industry. Most interviewees displayed wise optimism about emerging technologies such as AI, cloud computing, and fully integrated IoT systems as possibilities for further transformation of operations. Participant 2 commented, “I see a tremendous potential in adopting 4IR technologies that will eventually automate many maintenance tasks.” Albeit a brief remark, it is fully representative of a collective vision shared over the various interviews for this study.

Most of the interviewees noted that increased investments in advanced technology will not only build better operations but will also facilitate sweeping changes in regulatory practices. With real-time and predictive situational data, mining companies could soon be implementing more proactive safety and environmental protocols. As reported by Participant 5, “The more technology will be integrated into the value chain of production, the more we will see changes in health and safety regulations.” This tendency suggests that the general transformation of the whole industry will be brought forth by deepening technological adoption.

While much depends on the inherent optimism, the funding risks have not receded. Time and again, the high costs of installing and maintaining advanced technologies arose. Participant 13 summed it up as, “Adoption is slow because funding is a big barrier. Without proper funding, even the best technologies are underused.” The challenge implies that coordinated action should be taken against the underutilisation of technology innovations by the mining industry at the national or financial institutional levels.

Arguably, the other major element envisaged to change in the future is how the workforce will be developed. New generations entering the industry come with native digital skills, which promote an easier shift to technology. However, it is worth mentioning that the gap found in the current workforce due to a lack of technical skills will require significant work in educational and training programmes. Participant 8 stated, “Universities are now benchmarking their curricula to digital skills, which will help to close that gap in the future

workforce.” This statement reflects a trend toward a wider alignment of educational outputs with industry requirements.

All in all, technology’s future in coal mining is bright. However, it will depend on what funding challenges it can outrun, the strengthening of training programmes, and the upgrading of regulatory frameworks. Technology will no doubt change the approach of mining towards a more automated, efficient, and safe environment, provided investments and strategic planning are in place.

4.3 Chapter summary

This chapter presented the study findings in detail through a thematic analysis of interview data. The introduction explained the chapter’s overall structure and context, while the thematic analysis identified six principal themes. First is that the wide-ranging technological innovations—from process improvement, such as improved coal handling systems, to sensor and connectivity strategies—have been productive agents for change in mining operations. Second, real-time monitoring systems, together with predictive maintenance practices, have improved operational efficiency and reduced downtime, even though challenges persist. Third, training and knowledge management were among several significant challenges in implementation, along with cost limitations. Fourth, although technological innovations have resulted in improvements in environmental monitoring capacity, systems today are still largely reactive and require further automation. Fifth, the impacts on staff and local communities have been mixed, improving safety and efficiency, but on the flip side presenting problems with job security and the demand for highly advanced technical skills. Finally, the industry outlook is cautiously optimistic, with further technological integration expected but tempered by funding and regulatory issues. Overall, the findings demonstrate a complex interplay between technological advancement and its operational, environmental, and socio-economic fallout, paving the way for further discussions and recommendations in subsequent chapters.

CHAPTER 5: DISCUSSION, CONCLUSION, LIMITATIONS AND RECOMMENDATIONS

5.1 Introduction

The objective of this chapter is to bring together the main findings from the thematic analysis with other pieces of research to show how they transform the coal mining industry in South Africa. The first relationship under this chapter discusses the findings with some of the established theories and previous empirical studies, then presents conclusions drawn from research. This is followed by the study's limitations and thereafter practical as well as theoretical recommendations for future research and industry practice. Throughout this chapter, reference is made to seminal works (e.g. Bekun, 2024; Doe & Lee, 2022; Johnson et al., 2020; Matenda et al., 2024; Smith, 2021) to ensure that the discussion is grounded in relevant academic discourse.

5.2 Discussion of the findings

The results from this research have been discussed in the context of three objectives: evaluating the effects of technological innovations on productivity and efficiency, analysing the environmental impact of innovation practices, and assessing socio-economic impacts on local communities and peer groups. In furtherance, insights from interviews were joined with the literature to import a holistic analysis.

5.2.1 Impact on productivity and efficiency

It was found that process and digital innovations have been essential contributors to improving productivity and operational efficiency enhancement in coal mining in South Africa. Innovations in processes, such as extended production schedules—otherwise referred to as the “full coal system”—have enhanced operational hours and consequently increased output levels. Similarly, there have been real-time monitoring technologies such as sensors, underground Wi-Fi, and GIS systems that enable better management with more optimised inputs of a mining operation. Such systems have allowed for continuous sharing of data, predictive maintenance, and prompt remedial action during equipment malfunctions. These findings align with earlier studies by Doe and Lee (2022) and Johnson et al. (2020), who emphasise that real-time data collection complements minimising downtimes and enhances maintenance routines. In addition, Makgetla and Patel (2021) assert that the digital integration of underground operations with surface management significantly streamlines production

processes, a claim supported by our findings. However, interview data also revealed challenges in integration and adaptation by the workforce, indicating that the full-fledged benefits of these innovations would be realised only after adequate training and gradual imposition.

5.2.2 Environmental implications

Improvement in environmental management in coal mining has mushroomed due to modern technological innovation. The installation of environmental monitoring systems, especially sensors for water quality, dust, and emission monitoring, enhances its application in mining operations for impact management and mitigation. The findings of our study agree with Bekun (2024) who opines that no technological devices should be dispensed with for tracking and controlling ecological parameters, and Hassan (2023) who stresses the need for real-time monitoring solutions at the industrial level. However, research also indicates that most of the available environmental monitoring methods have remained reactive. Many of the respondents mentioned that although these ultramodern sensors and monitoring instruments had been installed, the systems still rely heavily on periodic sampling and laboratory analyses rather than offering continuous real-time data. This observation was captured by Omole et al. (2024) who asserts that the shift from reactive to proactive environmental management is essential to curb ecological damage. The study outcome emphasises a greater need for investment into automated and integrated environmental monitoring systems to get the best from such technical innovations in reducing the environmental footprint of mining activities.

5.2.3 Socio-economic effects on local communities and the workforce

The socio-economic impact of technological innovations constitutes a dimension of the research characterised by multifarious angles. The analysis shows that while worker safety is enhanced by digital technologies that reduce exposure to hazardous conditions, the flip side of such advances exhibits concern for job security and skill requirements. The recent shift toward automation using remote monitoring systems and digital communication tools has reduced the need for manual labour in operational areas with heightened concerns for possible job displacement. This echoes the findings of Cole et al. (2023) and Nel et al. (2023), who describe similar socio-economic transitions in mining communities. Additionally, the study shows technological innovations will set forth the demand for skill varieties. As real-time data analytics and digital tools penetrate mining operations, there will be a growing demand for technicians involved in instrumentation, data handling, and perhaps simple programming. On the aspect of upskilling, the need for such is stressed by Jamieson et al. (2023), who point out

that continuous professional development is key to adapting to technological change. In that sense, operational safety improvements are attributed to technological adoption because hazardous working conditions will be made minimally unsafe after several years of intervention. However, the remaining challenges are dependent on upskilling and education to avert deepening socio-economic disparities. Ultimately, this implies that technological innovation serves a dual purpose: first, for safety and productivity and second, for counteracting negative employment and community stability dynamics.

5.3 Conclusion of the study

The study concludes that technological innovations are playing a fundamental role in the transformation of the South African coal mining industry, albeit in a complex and often uneven manner. Literature supports the view that their effectiveness may result from the implementation of the full coal system as a process innovation, together with advanced technological tools such as sensors, underground Wi-Fi, GIS, and environmental monitoring systems, in enhancing efficiency and minimising downtimes, albeit with some exceptions (Johnson et al., 2020; Smith, 2021). Some of the crucial challenges that obtrude in the research include insufficient training, resistance to change, and high implementation costs, which interfere with the glory of the benefits.

Environmental monitoring technologies have given the industry a better chance of managing wastewater, dust, and emissions. Still, many systems remain proactive rather than reactive, indicating that further advancements in real-time monitoring and automation are warranted (Bekun, 2024; Hassan, 2023). Technological integration, while supporting safety and reducing workers' exposure to risks, has created skills and job security challenges within the workforce. The industry's future is embedded in tackling these challenges through effective change management, increased investment, and aligning educational outcomes with the needs of the industry (Cole et al., 2023; Matenda et al., 2024). To conclude, the coal mining sector is increasingly being embraced by driving forces of technological innovations. However, a sustainable advancement approach weighs the opportunities against the challenges.

5.4 Limitations

Despite much worthy information about technological innovation in the coal mining industry, several limitations exist. First, drawing data from a purposive sampling of industry stakeholders, the research relied on qualitative data, which may not adequately represent the diversity of experience across other mining operations in South Africa. Secondly, the results

are mainly rooted within a context, i.e., based on the lived experience of certain selected mines, which could lead to limited generalisability of the results to different regions or sectors. Thirdly, with the rapid advancement in the technology sector within the industry, findings may have become obsolete as newer technologies are introduced. Lastly, potential biases in self-reported data from the respondents and limited options for observational data might have influenced the outcomes of this study. Depending on future considerations, a mixed-method approach would serve well, since the study would benefit from a larger sample and a greater diversity of respondents, thus ensuring greater strength to its conclusions.

5.5 Recommendations

Based on the study's findings and in line with the literature, several recommendations are offered for industry practitioners, policymakers, and future researchers.

5.5.1 Enhance training and upskilling programmes

To address the challenges of knowledge management and resistance to change, mining companies should invest in comprehensive training programmes. As emphasised by Jamieson et al. (2023) and supported by our findings, continuous professional development is critical. Training should focus on both technical and digital skills to prepare the workforce for the complexities of new technologies.

5.5.2 Invest in integrated and automated systems

Given the reactive nature of current environmental monitoring systems, there is a need to adopt more automated, real-time solutions. Future investments should target IoT-enabled platforms that provide continuous data feeds and automated alerts to preempt environmental hazards, in line with recommendations by Omole et al. (2024).

5.5.3 Secure adequate funding

Funding remains a key barrier to technology adoption. Mining companies, in collaboration with government bodies and financial institutions, should explore innovative financing mechanisms and public-private partnerships to secure the necessary capital for technology investments.

5.5.4 Foster a culture of change management

Implementing technology successfully requires effective change management strategies. Organisations should designate innovation champions and create clear communication

channels to ensure that all stakeholders understand the benefits and operational changes associated with new technologies.

5.5.5 Policy and regulatory support

Policymakers should work with industry stakeholders to update regulatory frameworks that support technological innovation. This includes establishing guidelines for technology implementation, safety protocols, and environmental management standards, as discussed by Bekun (2024) and Hassan (2023).

5.5.6 Future research

Future studies should employ mixed-methods approaches to validate and extend these findings. Expanding the sample size and incorporating quantitative data could provide a more comprehensive understanding of the impact of technology in the mining sector.

5.6 Chapter summary

This chapter integrated the findings of the study with existing literature to consider how technological innovations have transformed the South African coal mining sector. The discussion pointed out that while technologies such as the full coal system, sensors, underground Wi-Fi, and GIS have improved operational efficiency and environmental monitoring, challenges in implementation, training, and funding still hamper widespread adoption. The conclusions drawn affirm that technological progress is important for sustainable mining but that the success thereof is contingent upon the balancing of issues such as worker readiness and capital constraints. The limitations regarding sample diversity and context specificity were acknowledged, with recommendations made for improvement of training, funding, automated system acquisitions, and updating the regulatory framework. Overall, the study paints a cautiously optimistic overview of technology's future in coal mining, suggesting that only by strategically intervening and researching further can its full potential be released.

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APPENDICES

APPENDIX A: WITS ETHICAL CLEARANCE



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16 January 2025
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PAG

Mr M Dzimbae
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Dear Mr Mmboneni Dzimbae

Master of Business Administration: Approval of Title

We have pleasure in advising that your proposal entitled *The impact of innovation in the coal mining industry in South Africa* has been approved. Please note that any amendments to this title have to be endorsed by the Faculty's higher degrees committee and formally approved.

Yours sincerely

A handwritten signature in black ink, appearing to read 'M Bosman'.

Mrs Marike Bosman
Faculty Registrar
Faculty of Commerce, Law and Management

APPENDIX C: INTERVIEW GUIDE

Interview Guide

1. Can you describe any technological innovations that have been implemented in your mining operations in the last five years?
2. How have these innovations affected operational efficiency in your mining processes?
3. To what extent has the adoption of technologies such as AI and IoT contributed to reducing operational downtime?
4. What challenges have you encountered in implementing these new technologies in coal mining operations?
5. How has automation and AI impacted the skill requirements for workers in your mining operations?
6. What role have technological innovations played in reducing the environmental impacts of your mining activities?
7. Can you discuss any specific technologies that have been adopted to monitor and mitigate environmental impacts?
8. How does your organisation measure the environmental impact of its mining activities before and after implementing new technologies?
9. In your opinion, are there any gaps in the current technological solutions used to mitigate environmental issues?
10. Have the technological innovations led to any unintended negative environmental consequences?
11. What have been the socio-economic impacts of technological innovations on local communities surrounding the mines?
12. How has the adoption of new technologies influenced employment patterns and job security in your mining operations?
13. Can you describe any community engagement initiatives that have been linked to the adoption of new technologies in your operations?
14. In what ways has technology adoption affected worker safety and health in your operations?
15. Looking forward, how do you see the role of technology evolving in the South African coal mining industry?

APPENDIX D: EDITOR'S LETTER

Napier
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26 February 2025

WITS Business School
University of the Witwatersrand
JOHANNESBURG

LANGUAGE & TECHNICAL EDITING

Cheryl M. Thomson

THE IMPACT OF INNOVATION IN THE COAL MINING INDUSTRY IN SOUTH AFRICA

This is to confirm that I, Cheryl Thomson, executed the language and technical editing of the above-titled research report of **MMBONENI DZIMBAE, student number 295586**, at **WITS BUSINESS SCHOOL**, in preparation for submission of this research report for assessment.

Yours faithfully



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