Evaluating Technological Awareness in South African Hard Rock Mining Operations

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Abstract
Hard rock mining contributes significantly to South Africa's gross domestic product and employment. As a pivotal component of the nation's economic framework, the sector encounters profound challenges threatening its stability and future growth. The sector's continued struggles with an alarming rate of accidents and health-related incidents highlight the urgent need for improvement. Emerging technologies (ETs), an attribute of Industry 4.0, offer numerous beneficial potentials as a strategic response to the sector's challenges. Hence, this study evaluates the awareness of ETs in the South African hard rock mining industry. A structured, closed-ended questionnaire survey was administered to respondents. The questionnaire comprised twenty-one (21) ETs identified through an extensive literature review. The collected data were then subjected to descriptive analysis. Findings revealed that proximity detection systems, facial recognition clocking systems, and wearable technology are the most well-known ETs. ETs are, therefore, key to improving the mining sector's safety, operational efficiency and sustainability.

Keywords
Africa, Emerging Technologies, Fourth Industrial Revolution, Mining Sector, Sustainable Development.

1. Introduction

The mining sector in South Africa has long been a cornerstone of the nation's economy, contributing significantly to its gross domestic product (GDP) and economic activity. Historically, the mining industry has contributed around 8% to the GDP annually, representing about 18% of total economic activity in the country (Antin, 2013; Rehman et al., 2020). However, this vital sector faces several critical challenges threatening its sustainability and efficiency, particularly in miner safety and rising operations costs. Safety remains a paramount concern within the South African hard rock mining context. The physical hazards miners encounter, including rockfalls and equipment malfunctions, pose a risk to life and threaten operational continuity and the industry's reputation (Koul & Eydgahi, 2017). The legal and moral obligations to ensure the safety of mine workers are compounded by the need to maintain a secure workforce in its working environment. Safe working conditions are also crucial in attracting and retaining skilled labour, as potential employees often consider personal safety a primary factor when choosing their place of employment (Ghani et al., 2022). Further compounding the challenges are the escalating costs associated with mining operations, particularly at deeper levels (Pimentel et al., 2016). Deep-level mining is fraught with increased hazards such as rock bursts and seismic activities, which require sophisticated monitoring systems and robust safety protocols. Additionally, the depletion of readily accessible mineral resources necessitates the extraction from more complex and remote locations, thus driving up operational costs. These financial pressures demand not only a reduction in expenses but also an enhancement of productivity, all while adhering to stringent environmental regulations and promoting sustainable practices.

In response to these multifaceted challenges, there is a burgeoning acknowledgement of the role emerging technologies (ETs) might play in transforming the industry. Innovations such as automation, robotics, artificial intelligence, the Internet of Things (IoT), and advanced data analytics, among numerous others, offer promising solutions that could significantly enhance safety measures, increase operational efficiency, and reduce costs, facilitating more sustainable practices. However, despite these potential benefits, adopting such technologies in the South African mining sector has been sluggish and fraught with hurdles. The reluctance to embrace these new technologies can be attributed to several factors, ranging from limited understanding of their benefits, lack of requisite technical expertise, resistance to change, concerns over high implementation costs, and fears regarding potential job losses. Hence, it is crucial to comprehensively assess the current state of technology adoption to overcome these barriers. This involves understanding the level of awareness among relevant stakeholders, identifying obstacles, evaluating the potential benefits, and developing strategies to promote effective integration of these technologies.

Given the urgency to address these persistent safety and operational challenges, the study explores the adoption of ETs within the South African hard rock mining sector. This study examines the awareness level of such technologies, considering their vast benefits in other sectors where they have been adopted and applied. Through the comprehensive exploration of the potential prospects of these technologies, the study aims to contribute significantly to the mining industry's knowledge base, offering valuable insights that stakeholders can use to leverage ETs for enhanced safety and operational efficiency. Doing so aims to provide actionable insights that can significantly improve industry safety standards and operational efficiencies through technological means. This streamlined objective sets the stage for an in-depth exploration of how ETs can be adopted and implemented to sustain and enhance the long-term viability of the South African hard rock mining industry.

2. Emerging Technologies in the Mining Sector

Emerging technologies are revolutionary innovations within a specific field that offer competitive advantages. They can be classified based on their types and applicable industries (Nisonen, 2012). In the context of the mining industry, emerging technologies have the potential to improve safety and operational effectiveness significantly. Mining becomes more costly and risky as mineral resources are depleted and the remaining reserves become deeper (Ediriweera & Wiewiora, 2021). Therefore, adopting emerging technologies has become a strategic necessity for South African mines to remain competitive and sustainable. Implementing emerging technologies in the mining industry comes with opportunities and challenges. While these technologies create new possibilities, they also introduce new problems that must be addressed (Giesing, 2003). To integrate emerging technologies successfully, the readiness of mining infrastructure must be assessed (Ali & Rehman, 2020). This evaluation ensures that the infrastructure meets the required standards for implementing technologies such as the Internet of Things (IoT) and asset management systems (AMSs), which rely on data storage and communication capabilities.

One of the key advantages of ETs in mining is the ability to monitor underground equipment remotely and detect early warning signs of potential dangers related to rock and ground behaviours (Dempsey et al., 2018). Communication systems play a crucial role in ensuring the safety and security of the underground mining environment, and emerging technologies provide opportunities to enhance the existing communication systems (Singh et al., 2018). To collect real-time data, it is essential to have equipment compatible with data collection. IoT sensors, for instance, can be utilised to gather data for analysis and prediction (Ayvaz & Alpay, 2021). Using machine learning algorithms, data generated from IoT sensors can be analysed to detect signals of potential failures before they occur, thus providing valuable insights for proactive decision-making (Giordano et al., 2022). In addition to safety and communication improvements, emerging technologies offer a wide range of applications in the mining industry. These technologies can optimise exploration processes, enhance ore extraction efficiency, and improve the overall productivity of mining operations (Zhu & Li, 2021). For instance, advanced imaging technologies such as hyperspectral imaging and 3D mapping enable accurate identification and characterisation of mineral deposits, aiding in selecting optimal mining locations (Vashistha, 2019). Automation and robotics play a significant role in increasing operational efficiency and reducing the reliance on human labour, particularly in hazardous or challenging mining environments (Pagliarini & Lund, 2017).

Furthermore, emerging technologies contribute to environmental sustainability in mining operations. For example, adopting renewable energy sources and energy-efficient practices can reduce carbon emissions and minimise the ecological footprint of mining activities (Onifade et al., 2024). Advanced waste management techniques, such as using tailings as construction materials or applying innovative recycling processes, enable the efficient utilisation of resources and reduce environmental impact (Fisher & Schnittger, 2012). Therefore, adopting ETs in South Africa and other developing countries' similar mining industries presents immense opportunities to enhance safety, operational efficiency, and environmental sustainability. Hence, carefully evaluating mining infrastructure readiness, awareness of ETs and collaboration among relevant stakeholders is necessary to implement these technologies successfully.

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3. Research Methodology

This study utilised quantitative research methodology to investigate the awareness level of emerging technologies (ETs) in the South African hard rock mining sector. The study focused on obtaining input from qualified and practising mining professionals in South Africa. These professionals included project managers, mechanical engineers, instrument engineers, mining engineers, metallurgical engineers, environmental engineers, health and safety managers, and electrical engineers, all actively involved in mining activities and projects. A simple random sampling technique was employed to ensure an unbiased selection process, allowing each mining professional an equal chance of being selected. This method was used to avoid the clustering effect inherent in cluster sampling, where the population is divided into sub-groups, and only a subset of each group is sampled.

Data was collected through a meticulously developed, closed-ended questionnaire distributed electronically via Google Forms. The questionnaire was divided into two sections: the first gathered demographic data, while the second contained 21 ETs identified through an extensive literature review. Respondents rated their level of awareness with each ET on a five-point Likert scale. To ensure the instrument's validity, a pilot study was conducted involving ten (10) carefully selected experts from the mining industry. Their feedback was instrumental in refining the identified variables, contributing to the reliability and relevance of the data collected. Upon completion, the returned questionnaires were meticulously reviewed and cleaned to ensure the accuracy and completeness of the data. The data were subsequently analysed using descriptive techniques. The descriptive analysis provided a broad overview of the professionals' awareness of the identified ETs, thereby offering deeper insights into the adoption and implementation issues around the technologies in the hard rock mining sector. The study yielded an impressive Cronbach's alpha coefficient of 0.937, signifying high internal consistency and reliability within the data collection instrument. This robust alpha value underscores the reliability of the questionnaire, thereby bolstering confidence in the precision and credibility of the results obtained from the respondents. Such a high level of internal consistency ensures that the instrument effectively captures the constructs under investigation, reinforcing the validity of the study's findings..

4. Findings and Discussions

4.1 Demographic Analysis of Respondents

Table 1 presents the demographic information of the respondents utilised for the study. From the Table, the professional qualification spread of the respondents re-vealed that mechanical engineers account for 38.8%, electrical engineers account for 22.5%, mining engineers account for 15.0%, environmental engineers account for 7.5%, metallurgical engineers and project managers both account for 5.0%, instru-ment engineers account for 3.8% and others (health and safety managers) account for 2.4%. Regarding the respondents' years of experience in the mining sector, 20 years and above account for 53.7%, 11-15 years account for 20.0%, 6-10 years account for 13.8%, and 16-20 years account for 12.5%. A total of 40.0% of the respondents are currently involved in 1-2 projects, 17.5% account for 3-4 projects, 8.8% account for 5-6 projects, 1.3% account for 7-8 projects, 6.3% account for those with more than 8 projects, while 26.1% account for those currently handling or engaged with no project. Most of the respondents work for the private sector, accounting for 92.4%. Those working for the public sector account for 3.8%, while those working with both private and public sectors account for 3.8%.

Table 1. Respondents' demographic information.

Factors	Variables	Percentage
Professional Qualification	Electrical engineers	22.5%
	Mechanical engineers	38.8%
	Instrument engineers	3.8%
	Metallurgical engineers	5.0%
	Mining engineers	15.0%
	Environmental engineers	7.5%
	Project managers	5.0%
	Others (health and safety managers)	2.4%
	Total	100%
Years of experience in the mining sector	6-10years	13.8%
	11-15years	20.0%
	16-20years	12.5%
	20 years & above	53.7%

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	Total	100%
Number of current mining projects	None	26.1%
	1-2 projects	40.0%
	3-4 projects	17.5%
	5-6 projects	8.8%
	7-8 projects	1.3%
	More than 8 projects	6.3%
	Total	100%
Sectoral affiliation of respondents	Private sector	92.4%
	Public sector	3.8%
	Public and private sector	3.8%
	Total	100%

4.2 Descriptive Analysis: Awareness Level of Emerging Technologies in the Hard Rock Mining Sector
Table 2 describes the respondents' awareness of emerging technologies in the South African hard rock mining industry. The respondents ranked their awareness level of the twenty-one identified ETs using a five-point Likert scale. On the Likert Scale, 1 = Not aware, 2 = Slightly aware, 3 = Moderately aware, 4 = Strongly aware, and 5 = Very strongly aware to establish the rank of respondents' scores. From Table 2, the proximity detection system was ranked first, with a mean score of 4.14 and a Standard deviation value of 1.076. The facial recognition clocking system was ranked second with a mean score of 3.70 and Standard deviation of 1.247; wearable tech-nology was ranked third with a mean score of 3.33 and Standard deviation of 1.357; 3D technology was ranked fourth with a mean score of 3.23 and Standard deviation of 1.253 while Internet of Things (IoT) was ranked fifth with a mean score of 3.20 and Standard deviation of 1.436. However, the least-ranked three ETs for the hard rock mining industry include autonomous irrigation, which was ranked nineteenth with a mean score of 2.14 and a Standard deviation of 1.270; stealth mining was ranked twentieth with a mean score of 1.76 and a Standard deviation of 1.034, and Arduino platform was ranked twenty-first with a mean score of 1.75 and a Standard deviation of 1.049.

As shown in Table 2, a Kruskal-Wallis non-parametric test was used to compare the respondents' awareness level of emerging technologies in the South African hard mining industry at a 95% significance level. The result also shows no statistically significant difference, with a p-value ranging from 0.081 to 0.888 in the respondents' perception towards twenty of the identified emerging technologies in the South African hard mining industry. Only the respondents' awareness level of robotic shaft and tunnel drilling was statistically and significantly different, with a p-value of 0.040. It is not surprising that proximity detection systems top the list of technologies well-known to mining professionals, as they are widely used in the sector (Agbolade et al., 2023; Chen et al., 2023). It is one of the technologies relied upon to ensure monitoring and safety in the construction and mining sector, owing to the high statistics of injuries and fatalities (Marks & Teizer, 2013). However, the weak mean values observed across the technologies presented align with the clamour for the mining industry to embrace and implement Industry 4.0 technologies to address the various challenges facing the sector (Sishi & Telukdarie, 2020). To also enhance productivity within the mining sector, the role of different innovative technologies cannot be overemphasised (Humphreys, 2020).

Table 2. Awareness level of emerging technologies in the hard rock mining sector.

Emerging Technologies	Mean Score	Standard Deviation	Rank	Chi-Square	Asymp-Sig
Proximity Detection System	4.14	1.076	1	9.247	0.223
Facial Recognition Clocking System	3.70	1.247	2	8.836	0.265
Wearable Technology	3.33	1.357	3	8.156	0.319
3D Technology	3.23	1.253	4	12.449	0.087
Internet of Things (IoT)	3.20	1.436	5	5.359	0.616
Drones	3.19	1.223	6	1.650	0.977
Artificial Intelligence (AI)	3.13	1.247	7	7.156	0.413
Virtual Reality (VR)	3.11	1.378	8	12.666	0.081
Hydrogen Powered Vehicles	2.99	1.401	9	5.4570	0.604
Autonomous Drilling System	2.80	1.354	10	11.749	0.109
Autonomous Mining Systems	2.78	1.350	11	7.2730	0.401
Robotics	2.70	1.205	12	9.181	0.240
Augmented Reality (AR)	2.49	1.283	13	3.791	0.804
Robotic shaft and tunnel drilling	2.45	1.321	14	14.728	0.040*
Nanotechnology	2.38	1.257	15	5.623	0.584

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Building Information Modelling (BIM)	2.34	1.201	16	4.428	0.729
Automated Tunnel Reinforcement	2.33	1.230	17	2.971	0.888
Gravity Gradiometer	2.21	1.240	18	6.340	0.501
Autonomous Irrigation	2.14	1.270	19	6.306	0.505
Stealth Mining	1.76	1.034	20	6.026	0.537
Arduino Platform	1.75	1.049	21	3.677	0.816

5. Conclusion and Recommendations

This study sets out to assess the awareness level of emerging technologies in the South African hard rock mining sector, leveraging the opinions of mining professionals. The objective was achieved by adopting the quantitative method of research with a well-structured questionnaire survey administered to mining professionals in South Africa. The retrieved data were subjected to descriptive analysis. The study showed that several technologies are well-known to the mining sector, while others remain in the dark, limiting their adoption and implementation. This study underscores the importance of ETs in enhancing operational efficiency, safety, and sustainability within the mining sector. The results indicate that while awareness of ETs such as proximity detection systems (PDS), facial recognition clocking systems, wearable technologies, 3D technologies, Internet of Things (IoT), drones, artificial intelligence (AI), and virtual reality (VR) is high and increasing, there remains a significant gap between awareness and full-scale adoption and implementation. This gap can be attributed to factors such as the high costs of technology integration, limited technical expertise, resistance to change, and, most importantly, the traditional perception that technologies will take away jobs and human-centric operational frameworks.

In conclusion, while there is a growing recognition of the potential benefits of ETs in improving productivity, reducing operational risks, minimising injuries and accidents and ensuring environmental compliance, the mining sector must overcome several barriers to fully leverage these advancements. For South Africa to remain competitive on the global stage, a more coordinated effort is needed, involving collaboration between government, industry stakeholders, and research institutions to optimise these technologies that have now characterised the fourth industrial era. This will ensure that the sector not only increases awareness of innovative technologies but also fosters a culture of adaptation and implementation, skilling, reskilling, continuous professional development, and training of workers. Furthermore, by increasing awareness of ETs and their utilisation, the mining sector will also be able to function in the face of pandemics such as COVID-19, thereby ensuring unhindered productivity and sustainability. Targeted skills development and infrastructure investments are recommended to bridge the current gap and position the mining sector for future technological advancements on par with its counterparts in developed economies.

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