



Publisher
Sustainability for Regions



APPLICATION OF FOURTH INDUSTRIAL TECHNOLOGIES: A CASE OF ZIMBABWE'S MINES

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Received 10 September 2024; accepted 3 December 2024; published 30 December 2024

Abstract. The Fourth Industrial Revolution (4IR) dispensation has revolutionised mining activities globally. New technologies and automation, among others, have been introduced into the exploration, quarrying, mining and extraction of minerals in underground and open pit mining in developing countries like Zimbabwe. However, some impediments exist to adopting and operationalising 4IR technologies in Zimbabwe's mining sector. In light of this, the study examines the challenges and prospects underpinning the adoption and operationalisation of 4IR technologies in Zimbabwe's mining sector. Due to its qualitative nature, the study was based on a thorough examination of textual materials that were specifically chosen, including books, newspaper articles, government publications, journal articles, and book chapters. The study purposively selected Zimplats Mine, Unki Mine, Murowa Diamonds, Mimosa Mine, Freda Rebecca Mine and Caledonia Mining Group as the units of analysis. The obtained data was examined by applying content and thematic analysis methods. According to the study, various mining companies in Zimbabwe use various 4IR technologies in their respective mining activities, such as automated drilling and loading systems, digital twin technology, Internet of Things (IoT) devices and remote sensing, artificial intelligence (AI)-driven data analytics, automation, machine learning, and cloud computing, at varying degrees and stages. These technologies are crucial in enhancing productivity, efficiency, safety, decision making and cost reduction in Zimbabwe's mining sector. However, the study established that the implementation and adoption of 4IR technologies in Zimbabwe's mining sector needs to be improved because of a lack of capital, the absence of digital infrastructure, resource immobility, and the unavailability of necessary talent and skills, among others. To address the identified challenges, the study recommended that there is a need for the development of 4IR infrastructure, enactment and strengthening of 4IR supporting policy and regulatory frameworks, capacity building and training, collaborations and partnerships, supporting research and development (R&D) initiatives, and awareness campaigns and stakeholder engagement.

Keywords: Fourth Industrial Revolution; mining sector; challenges; prospects; Zimbabwe

Reference to this paper should be made as follows: Chilunjika, A. 2024. Application of fourth industrial technologies: a case of Zimbabwe's mines. *Insights into Regional Development*, 6(4), 124-140. <http://doi.org/10.70132/a2354787553>.

JEL Classifications: O3, O31, Q5, Q32

1. Introduction

One of the main drivers of the Zimbabwean economy, both socioeconomically and in terms of human development, is the mining industry. However, according to the Chamber of Mines of Zimbabwe Report (2022), many mines in Zimbabwe are having trouble operating due to issues like lowcapacity utilisation, outdated equipment, poor safety performance, resource depletion, foreign exchange shortages, capital shortages, high costs, and power outages. Today's mining operators face a triple threat of deteriorating ore grades, growing operational costs, and decreasing operating efficiency, regardless of the commodity they are mining. Given the wide variations in ore bodies and mining activities, handling such issues in the mining environment is challenging. The need for expensive, capital-intensive infrastructure, long planning horizons, and protracted implementation schedules exacerbates this, not to mention the inherent risk in the operational settings that raise essential safety

concerns. Because of this, it has been challenging for Zimbabwean mining corporations to perform above expectations.

Since its inception in 2016, Zimbabwe Consolidated Diamond Company (ZCDC) has been operating at a loss due to low diamond prices and the high cost of conglomerate mining. Shamva Gold Mine and Redwing Mine stopped operations and were placed under care and maintenance due to the high cost of production and deep-seated ore deposits. According to the ZCDC Annual Report 2022, there is a general decline in productivity in Zimbabwe, a mining capacity utilisation rate below 70%, and an increase in lost time due to accidents and fatalities in various chrome, platinum, and gold mines. In the mining sector, there were 116 fatal incidents in 2019 as opposed to 81 in 2018. This figure includes accidents from small operations, including illegal mining operations. As indicated above, mining capacity utilisation in Zimbabwe's diamond, platinum, and gold mines has significantly dropped in 2019 to below 70% due to electrical power cuts being experienced in the country. This has resulted in low productivity and a high cost of doing business as an alternative source of electricity supply from generators is not sustainable due to the high set-up cost as mining is a heavy user of electricity. The mining sector faces other challenges, such as global competition with mines that can produce at low cost, skills shortage, and exhausting benefits of economies of scale (Chipangura, 2019; Mpafa, 2028; Goldcorp, 2017; Dube, 2016). It has, therefore, seemed like a noose around these problems for mines. They find it difficult to implement significant, company-changing changes if they lack true visibility and access to timely, accurate, and comprehensive data or business options. Mines continue to use outdated strategies, sweating their meagre resources and exerting more effort for meagre rewards. The outcome is a reactive response and poorly informed decisions.

Innovation in the mining industry is still desperately needed to address the industry's problems. Automation, digitisation, and electrification are just a few of the rapid breakthroughs in digital technological innovation that significantly influence the mining sector. Global positioning systems (GPS), offsite control centres, automated tunnel-drilling machines, drones, smart sensors, wearable technology, and machine learning are just a few of the new technologies currently revolutionising the industry. Examples include autonomous machines like loaders, road trains, and dump trucks (Baumann, 2020; Deloitte, 2018; Koziol et al., 2018). Numerous such technologies are ideally suited for integration inside the mining cycle. Automation enables businesses to take workers out of hazardous work environments. The Fourth Industrial Revolution (4IR), which has witnessed the exponential digitalisation and the adoption and usage of technology, is influencing the future of mining. In recent times, there have been notable reductions in the cost of technology accompanied by advancements in machine capabilities, robotics and automation, data collection, processing, storage, artificial intelligence, and crucial human-machine interaction.

The digital transformation of corporate processes brought about by the Fourth Industrial Revolution has already resulted in performance advantages for early adopters such as Rio Tinto Pilbara Iron Mine, Goldcorp Mine, and Dundee Precious Metals (Canada). According to the World Economic Forum (2018), autonomous machines are expected to become mainstream by 2025. Having these machines run around the clock, with higher productivity and lower labour costs, could raise the mining industry's worth by approximately USD 56 billion. Similarly, Deloitte (2018) projects that the mining industry could benefit USD 34 billion from using smart sensors by enabling predictive maintenance, increasing equipment utilisation, decreasing equipment failures and downtime, and reducing the frequency of health and safety incidents. Rio Tinto's Mine of the Future program was launched in 2008 and has achieved significant automation gains since its establishment. The program was founded to assist the miners in finding innovative ways of extracting minerals while reducing environmental impacts and improving worker safety. The cumulative effect has been reduced costs and increased productivity; the cost savings from automation have made the company more resilient to highs and lows in commodity prices while also helping to make Rio Tinto the lowest-cost iron ore producer in the Pilbara region (Rio Tinto, 2020). Zimbabwean mining firms progressively use 4IR technologies to increase productivity, efficiency, and safety (Kaelo, Madyira & Nyemba, 2020; Mutandwa & Genc, 2018). These technologies include automation, artificial intelligence (AI),

the Internet of Things (IoT), and data analytics. Numerous mining firms in Zimbabwe have begun using these technologies in their business processes. Unki Mine adopted a Centralised Blasting System by integrating electronic blasting, the Internet of Things, a Radio Frequency Identification System (RFIS), and blasting (Responsible Mining Index, 2022). The digital innovation shift is imperative for any business's success and survival.

Zimplats started its digital transformation journey in the early 2010s and considerably increased its efforts in the middle of the decade. Zimplats Holdings Ltd has equipped its underground mines with automated loading and drilling systems. They also optimise production operations and predictive maintenance using AI-driven data analytics (Zimplats, 2023). To increase operating effectiveness and safety, Mimosa began incorporating 4IR technology in or around 2015. Mimosa Mining Company monitors and controls mining operations using IoT devices and remote sensing technology. They also employ cutting-edge mine planning and design software, guaranteeing efficient extraction procedures. Early in the decade, Caledonia prioritised digital modelling and predictive analytics when implementing 4IR technologies. In its operations, Caledonia Mining Corporation (Blanket Mine) uses AI, machine learning, and digital twin technology (Caledonia Mining Corporation Plc, 2019). They build virtual representations of their mining operations using the digital twin technology. Resource estimation and ore grade prediction are also done using AI and machine learning techniques. Since the early 2010s, RioZim Limited has been utilising 4IR technology, and there have been notable breakthroughs within the last five years (Rio Tinto, 2020). Some of RioZim Limited's operations now use automated mining equipment. They also streamline operational workflows and supply chain management with big data analytics. Against this backdrop, this study examines the dynamics surrounding the adoption and implementation of 4IR technologies on the performance of mining businesses in Zimbabwe.

2. Literature review

Fourth Industrial Revolution and Industry 4.0 are terms used interchangeably to denote the new paradigm of technological advances currently being experienced globally. The 4IR dispensation is characterised by technologies that bring together digital, biological, and physical spheres. In light of this, Haurovi and Chilunjika (2024) characterised the 4IR as technological advancements that bridge the gap between digital, biological, and physical spheres. The technologies include robotics, cloud computing, IoT, artificial intelligence (AI), and additive manufacturing (3D printing). According to Gilchrist (2016), four disruptions—the rise in big data, computing power, and connectivity; the development of analytics and business-intelligence capabilities; new methods of human-machine interaction; and augmented reality—are responsible for the stages of the digitalisation of the manufacturing sector.

From the above, it can be noted that there is no universally agreed definition of the 4IR. However, in its complexity, all scholars point to the new paradigm or revolutionary development and application of physical, digital, and biological technologies that have a disruptive impact on economies, society, business, nations, and the global sphere. Over and above, it is prudent to define 4IR by unpacking the cross-cutting, uniform and diverse characteristics of 4IR, which, as noted by Loshkareva, Luksha, Ninenko, Smagin & Sudakov (2017), recognised the essential attributes of 4IR, which are:

- the transition from difficult work to the automation of production processes,
- transformation of transport and strategic frameworks brought about by the mass introduction of automated vehicles,
- advancement in sophistication and accuracy of technical products because of the progress of industrial innovations,
- development of a machine-to-machine correspondence and self-administration of cyber-physical physical systems enabled through IoT,

- application of machine learning and artificial intelligence programmes for the provision of continuous improvements of production processes.

In light of this, 4IR is generally characterised by digitisation, streamlining, and customisation of creation; robotisation and variation; human-machine connection; esteem-included administrations and stores; and continuous data trade and correspondence.

Rapid developments in digital technology, such as automation, digitisation, and electrification, are significantly influencing the mining sector. A few of the new technologies that are currently revolutionising the industry are autonomous machines (such as trucks, loaders, drilling rigs, and road trains); offsite equipment operating control/centres; drones; smart sensors; wearable technology; and machine learning (Deloitte, 2018; Schwab, 2016). Big data and high-tech computing are expected to bring the most significant contribution to production through the creation of smart mining. These will generate real-time data in the mining value chain, and that data is mined and used to achieve efficient production, lean operations, reduced breakdowns, increased safety, and productivity. Gorman and Dzombak (2018) predict that using Fourth Industrial Revolution technologies will enable enterprises to achieve a roughly 30% boost in productivity. To quickly take advantage of all available opportunities, the integration of 4IR helps managers make timely decisions.

The commodity cycle, cost, and productivity constrain mining companies, and no savings will be left for re-investments. Innovation through fourth-industrial revolution technologies is needed to deliver the next phase of disruptions that transform business models and bring improvements (Deloitte, 2018). Bhowan-Rajah (2020) asserts that digital capabilities have enormous potential to generate value by developing lean processes. To create lean operational systems, decision-making must be improved, processes must be automated to improve systems, and design waste must be eliminated by employing digital technologies to create new assets. In addition to lowering costs and increasing productivity, the 4IR offers a fantastic chance to build stronger bonds with stakeholders, promote training and knowledge exchange, open up new markets, create new revenue streams, and create a safe working environment for employees (Bliss, 2018). In the mining industry, 4IR also includes the usage of digital twins, blockchain, automation, big data analytics, and the Internet of Things (IoT).

Automation causes workers to be replaced, creating a need for new skills. Employee upskilling will become increasingly important as automation takes the place of labour. Human capital with creative skills is this stage's most important production factor. Automated trucks reduce the cost of operation because they operate more efficiently, have shorter cycle times, lower fuel consumption, and reduced wear and tear, as well as enhanced employee safety (Mekonnen & Islam, 2021; Kaelo et al., 2020; Brynjolfsson & McAfee, 2014). Automated equipment like drones is used in mines for measuring stockpiles, security surveillance, and environmental monitoring and maintenance activities in waterlogged areas like slime dams and mountain peaks where the terrain is dangerous for humans to access. Big data is a word that is used to define data that is in large volume, high velocity, and large variety, requires innovation and strategies to gather, store, and process it and is used to achieve better decision-making, provide knowledge, find, support and optimise processes (Schumacher & Erol, 2020; Tapia, 2020; Bliss, 2018; PwC, 2017). According to Chilunjika et al. (2022), the IoT is a term for devices installed with a chip, sensor, radio frequency identification tags (RFID), or other tools used for system control to capture and transmit data. The mining industry may benefit from applying sensors and the Internet of Things with better predictive maintenance, longer equipment lifespans, fewer equipment malfunctions and breakdowns, and fewer health and safety problems. To improve coordination and response times, mining companies are also using cutting-edge communication networks, which include wireless and satellite technology, to enable real-time contact between workers and management (Chilunjika, Intauno, Poshai & Chilunjika, 2024; Bhowan-Rajah, 2020; Kaggwa, 2018).

Similarly, mining companies also use digital twin technologies to build virtual equivalents of actual resources and procedures and enable real-time mining operations monitoring, modelling, and optimisation. According to Bliss

(2018), workers can obtain training in a safe, controlled environment that replicates real-world scenarios, improving their skills and knowledge of safety by utilising virtual reality and augmented reality (VR/AR) technologies. Lastly, mining businesses may monitor their impact and enhance sustainability policies using blockchain technology, which can track and record environmental data. Waste management, energy use, and emissions are some examples of this data (Chilunjika & Uwizeyimana, 2024).

3. Methodology

This study, being qualitative, was informed by the interpretive research philosophy. Data was gathered from purposively selected written records such as journals, book chapters, books, newspapers, and government publications. The paper examined Zimplats Mine, Unki Mine, Murowa Diamonds, Mimosa Mine, Freda Rebecca Mine and Caledonia Mining Corporation as the units of analysis and data regarding these mining companies was collected. These data sources were reviewed and analysed to assess the challenges and prospects of deploying 4IR technologies in Zimbabwe's mining sector. Firstly, the author undertook a global search for papers that explored 4IR technologies and mining, which produced 200 sources or documents from different websites such as Google Scholar, Research Gate, Web of Science and the specific websites of mining companies. The author did the initial screening, which excluded 89 articles. A total of 111 publications were left after the initial screening. The author then did the final screening exercise, which filtered 29 sources and left 82 publications dealing with 4IR technologies, the Zimbabwean mining sector, and the selected mining companies in Zimbabwe (See Figure 1 below). These 82 publications were the key sources of information used to shape the study and generate the research findings. Following the completion of the investigation, content and thematic data analysis were performed on the collected data to categorise them into themes by determining the presence of words, themes, or concepts in the qualitative data (see Figure 1).

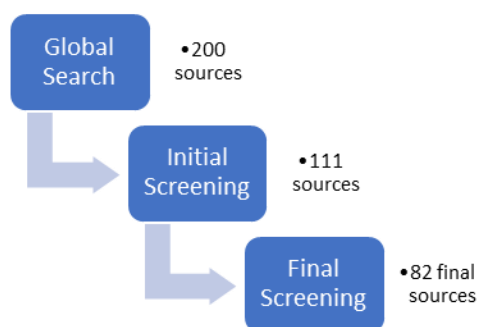


Figure 1. Selection of sources

Source: Author's construction.

4. Presentation and analysis of research findings

This section first paints a clearer picture that illuminates the different dimensions of the selected mining companies. The section explores the various technologies used by different mining companies in Zimbabwe and how they resonate with the 4IR dispensation. The section also highlights factors that encumber the adoption and operationalisation of 4IR technologies in Zimbabwe's mining sector.

Understanding the selected mining companies

The paper examined Zimplats Mine, Unki Mine, Murowa Diamonds, Mimosa Mine, Freda Rebecca Mine and Caledonia Mining Corporation as the units of analysis. In light of this, the paper explores these mining companies' location, ownership, financial indicators, and export destinations.

Zimplats Mine is situated close to Ngezi, on Zimbabwe's Great Dyke, around 150 kilometres southwest of Harare (Mpafa, 2018). The Great Dyke is a mineral-rich geological structure that is well-known for its substantial platinum group metal (PGM) deposits. Eighty-seven per cent of Zimplats Holdings Limited, the holding company for Zimplats Mine, is owned by Impala Platinum Holdings Limited (Implats), a platinum producer in South Africa. Under Zimbabwe's indigenisation effort, indigenous Zimbabwean stakeholders own the remaining 13%. Zimplats hold a majority stake in Zimplats Holdings despite the company being listed on the Australian Stock Exchange (ASX). Primarily, Zimplats exports rhodium, palladium, platinum, and various byproducts like cobalt, nickel, and copper (Denhere & Mhlanga, 2023). Most of these metals are exported to South Africa, Europe, China, Japan, Canada, and the USA. Over 580,000 ounces of platinum and substantial amounts of palladium, rhodium, and other metals are produced from the approximately 6.7 million tonnes of ore that Zimplats generates each year (Zimplats, 2023). Rising PGM prices, particularly for rhodium and palladium, have helped Zimplats maintain its substantial profit margin. Zimplats' profitability has substantially contributed to Implats' total earnings.

Situated on Zimbabwe's Great Dyke, some 32 kilometres west of Zvishavane, a mining town in the Midlands Province, is the Mimosa Mine, a platinum group metals (PGMs) mine (Chikande, Phillips and Carwood, 2021). Two of the world's biggest producers of platinum, Impala Platinum Holdings Limited (Implats), and Sibanye-Stillwater Limited, a precious metals mining corporation based in South Africa, jointly own Mimosa Mine. These two businesses administer the mine together as a joint venture with a 50:50 share arrangement. The main destination for Mimosa Mine's platinum group metal exports is abroad. Major markets for it are Europe, Asia (China and Japan), and North America, where it is utilised in the high-tech, jewellery, electronics, automotive, and aerospace industries (Loow, 2022; Manjenjema, 2018; Wilson & Prendergast, 2001). Mimosa has been producing about 120,000 ounces of platinum per year in the past few years and other PGMs like gold, rhodium, and palladium (CoMZ, 2022). The prices of platinum, palladium, and rhodium, which are very susceptible to changes in the global market, are the main drivers of the revenues. To increase productivity and lengthen mine life, continuous investments are being made in infrastructure, mining equipment, and potential expansions.

The Unki Mine, situated in Zimbabwe's Midlands Province, is a platinum group metals (PGMs) mining facility close to Shurugwi (Chaumba, 2017; Masuku and Ndlovu, 2014). It is situated on the mineral-rich Great Dyke, a region of the earth recognised for its enormous PGM reserves. Anglo American Platinum Limited, or Amplats, is the sole owner of Unki Mine in terms of ownership structures. As a part of the larger Anglo American Plc, Amplats is one of the world's top producers of platinum. According to Khawaja (2022), besides being used in industrial applications and high-tech industries like electronics, aerospace, and environmental control technologies, platinum and other PGMs from Unki Mine are mainly exported to international markets. Major destinations for these exports include Europe, China, Japan, Canada, and the automotive industry for catalytic converters. Palladium, rhodium, and other byproducts are also produced at Unki Mine, which usually yields 200,000 to 210,000 ounces of platinum annually (Anglo American, 2024). The need for PGMs, especially in the automotive and industrial sectors, and the worldwide price of platinum are the main drivers of revenue. Changes in the prices of rhodium, palladium, and platinum can significantly impact revenue.

The Murowa Diamonds Mine is situated in the Midlands Province of southern Zimbabwe, close to Zvishavane. It is well recognised that the mine produces excellent gem diamonds. RioZim Limited entirely owns Murowa Diamonds Mine. Rio Tinto originally owned a large portion of the mine, but in 2015, it withdrew from its

activities in Zimbabwe. The mine has been owned by RioZim, a mining company based in Zimbabwe, ever since. The main export markets for Murowa Diamonds are the United States, Belgium (Antwerp), China, and India. The value of a diamond is determined by its size, quality, and clarity (Casey, 2020). Murowa Diamonds exports rough diamonds through auctions and sales in several international diamond trade centres. In the past, Murowa has produced more than 500,000 carats of diamonds every year (RZM Murowa, 2021). Depending on operating circumstances and expansion initiatives, production levels may change. To cut operating expenses, the mine is making investments in efficiency upgrades. Modernising the processing plants and increasing production capacity are just two infrastructural upgrades RioZim has been concentrating on.

The Freda Rebecca Mine is situated in Zimbabwe's Mashonaland Central Province, not far from Bindura. With a long history of producing gold, it is the nation's most prominent individual gold mining operation (Zimbabwe Economic Policy Analysis and Research Unit-ZEPARU, 2016). Through its subsidiary Kuvimba Mining House, Sotic International, an investment company established in Mauritius, owns the Freda Rebecca Mine. The Zimbabwean government owns a minority part in Kuvimba, a joint venture, estimated at 65% by Sotic and 35% by the government of Zimbabwe. The main commodity that Freda Rebecca Mine exports is gold, which is exported internationally. South Africa, the United Arab Emirates, Switzerland, China, and India are important export markets (Ministry of Mines and Mining Development, 2019; Abrahamsson, Johansson and Johansson, 2009). Gold is sold on global markets, frequently via the London Bullion Market Association (LBMA). Over 50,000 ounces of gold are produced by Freda Rebecca each year, and different optimisation techniques are consistently being implemented to boost production (Goldcorp, 2017; Mlambo, Ndamba & Musvovi, 2017). To extend its life and boost its reserves, the mine has continuously invested in exploration efforts and infrastructure improvements. Improving production capacity and recovery rates has been the main focus of recent expenditures.

Situated roughly 150 kilometres southwest of Bulawayo, in the Matabeleland South Province of Zimbabwe, is the Gwanda Greenstone Belt, home to Caledonia's Blanket Mine (Xueqan, 2019; Musingwini, 2016; Mabhena & Moyo, 2014). This mine produces a significant amount of gold for Zimbabwe. Through its subsidiary, Caledonia Holdings Zimbabwe Limited, Caledonia Mining Corporation Plc holds a 64% ownership stake in Blanket Mine. As part of Zimbabwe's indigenisation program, the remaining 36% is owned by three native Zimbabwean stakeholders: the National Indigenisation and Economic Empowerment Fund (16%), the Blanket Employee Trust Services (10%), and the Gwanda Community Share Ownership Trust (10%). According to Zulu (2016), the mine is run by Caledonia, which has invested much in its modernisation and expansion. Gold is the main product that Blanket Mine produces and exports. China, India, South Africa, and Switzerland are important export markets. In 2022, Blanket Mine achieved a record output level of 80,775 ounces of gold, and the mine has set its sights on further expansion. The mine's continuous development programs are intended to yield over 90,000 ounces annually (Caledonia Mining Corporation, 2021). The fluctuations in global gold prices, which are influenced by economic conditions, geopolitical events, and market demand, directly impact revenues. Caledonia Mining Corporation recorded approximately \$121 million in sales in 2022.

Technologies used in Zimbabwe's mining sector

It can be noted that different mines in Zimbabwe are using diverse 4IR technologies, which include automated drilling and loading systems, artificial intelligence (AI)-driven data analytics, IoT devices and remote sensing, digital twin technologies, and advanced mining planning software, among others. To start with, automation is primarily utilised in most mines in Zimbabwe. ZCDC uses drones for security surveillance in Chiadzwa diamond fields, where the area is costly, to curb illegal diamond mining (ZCDC, 2021). Also, drones are being used to survey stockpiles and tailings dams, where there is a safety risk of drowning in muddy pools and falling off heights. Accordingly, Anglo American (2021) noted that Zimplats and Unki mines already use IoT underground to control blasting and collision of machine to machine and machine to people. Every piece of equipment is equipped with sensors, and employees use tags with sensors that alert them of approaching equipment in blind

spots underground. These have reduced vehicles to employee safety incidents. IoT at Unki mine has transformed how blasting is conducted (Anglo American, 2021; Initiative for Responsible Mining Assurance-IRMA, 2021; IRMA, 2016). Blasting efficiency and elimination of misfires were largely impacted. With central blasting systems, blasting will only happen if people and machines are evacuated from the blasting zone. Using the IoT, every blasting explosive detonator has a sensor. If holes are not connected to the circuit, it will lead to a misfired explosive, the system will raise the alarm, and correction will be made, avoiding costly reworks in treating the misfires.

Accordingly, RZM Murowa (2018) highlighted that Murowa Diamonds employs big data and analytics through Opsdata software, which acts as a digital information centre for diamond mine operations. This application was code-named "The Only One Version of the Truth". Data is input from departments into the central server. This information capture and analysis system connects machines, motors, trucks, and plants. A dashboard of hourly mining and processing production updates is displayed on a big screen in the common room area where everyone can see. This allows for visual operations management as real-time production statistics are tracked. Hence, real-time data-based management decisions are made for enhanced business performance (RZM Murowa, 2021). Other mines employing big data analytics include Zimplats, Unki Mine, and Mimosa mines. However, in some other mines, data are captured on Excel spreadsheets, and everyone can access no single data repository. The Internet of Things (IoT) is thought to have the most significant influence on businesses since it links the digital and physical worlds by gathering, measuring, and analysing data to forecast and automate commercial processes. From the literature review and the study, big data analytics, the IoT, cloud computing, and automation seem to be dominantly adopted in the mining and manufacturing industries currently and in the future globally (Chikande, 2022; Ndlovu, Ngwane & Mongae, 2022; Casey, 2020; Ministry of Mines, 2016).

Unki Mine in Zimbabwe has a Centralised Blasting System that employs 4IR technologies like sensors, Radio Frequency Identification tags (RFIT), and IoT. Underground workers, vehicles, and mobile units are fitted with RFIT, allowing the company to locate employees or equipment underground during evacuation for blasting. According to Xinhua (2021), electronic gas detector sensors read gas levels after blasting for safe re-entry into the mine. Connected electronic delay detonators allow miners to identify defective or unconnected holes, which improves blasting efficiency and saves time. The impact has been increased productivity, cost-saving, and reduced blasting-related safety incidents like misfires and gassing of employees. Every piece of equipment is equipped with sensors, and employees use tags with sensors that alert them of approaching equipment in blind spots underground. These have reduced vehicles to employee safety incidents.

Additionally, IoT at Unki mine has transformed the way blasting is conducted. Sensors are equipped in underground tunnels to monitor blasting fumes clearance before production can resume. Levels of toxic gases underground are observed from the control room. Re-entry will be allowed if the poisonous gas level is below permissible quantities; hence, no fatalities related to inhalation of toxic gases or carbon monoxide.

According to Gilchrist (2016), the IoT provides better visibility and knowledge of the organisation's activities and resources by incorporating equipment sensors, software packages, and cloud computing services. Advanced analytics of large volumes of collected data is done. Business benefits are accomplished through reduced breakdowns, increased efficiency, increased productivity, and hence profitability. Mpofu and Nemashakwe (2023), state that, in manufacturing, the IoT technology can improve operational efficiency in various ways. In manufacturing processes, inventory flow and supply chain tracking can be monitored through sensors to achieve reduced waiting times, improved transparency, and workflow optimisation. Automation is mainly being utilised in most mines in Zimbabwe. At Freda Rebecca Gold Mine, remote-controlled loaders are commonly used in mining dangerous stops in bad ground (Global Data, 2023; Mining Data Online, n.d). The automated drilling and blasting technology used in the mine reduces the need for manual labour while improving safety and precision. To increase efficiency and accuracy, the mine also uses robotic process automation (RPA) for repetitive operations

like data entry, equipment monitoring, and maintenance scheduling (Global Data, 2023). To maintain the integrity of the gold from the mine to the market, Freda Rebecca Mine also uses blockchain technology to improve supply chain transparency and traceability. Given this, Chilunjika and Uwizeyimana (2024) pointed out that smart contracts on blockchain systems save administrative overhead and boost stakeholder trust by automating and securing contract execution.

Nonetheless, it can be noted that automation in the mining sections of the value chain of the narrow gold reefs cannot be attained since the tunnels are too small to fit automated machines. For moderate widths platinum orebodies mines like Unki Mine and Zimplats, low-profile drilling rigs and dumps trucks are designed to fit in narrow to medium-height/width orebodies (Chikande, 2022; Casey, 2020; Chaumba, 2017). Moreover, processing operations, surveys, and other support functions remain open to automation. As noted above, using drones also falls under automation in mining. Drones can measure inventories, help with environmental and maintenance tasks, and lower worker dangers (Rio Tinto, 2017).

Similarly, 4IR technologies have been gradually incorporated into Caledonia Mining Corporation's Blanket Mine to improve operations. According to Caledonia Mining Corporation Plc (2021), Blanket Mine uses digital twin technologies that allow for the real-time monitoring of mining operations, scenario analyses, and simulation of mining operations. AI and machine learning are also used for ore grade prediction, predictive maintenance, and the optimisation of mining production processes. There is also the use of automated drilling rigs, automated drilling and loading of haulage trucks, and remote operations. Blanket Mine also employs IoT in its operations, whereby IoT sensors for real-time monitoring of mining operations parameters are utilised, as well as 3D modelling and optimised extraction technologies. By and large, with the utilisation of advanced planning software, digital twins, AI, automation, and IoT, the mine presents itself as a forward-thinking enterprise that can fulfil the demands of contemporary mining while maximising profitability and sustainability (Caledonia Mining Corporation Plc, 2019). Despite the usage of these diverse 4IR technologies in different mining companies in Zimbabwe, there are some impediments to the full adoption and seamless operationalisation of such technologies in Zimbabwe.

Barriers to the adoption of 4IR technologies in Zimbabwe's mining sector

Challenges in implementing 4IR digital technologies in most mines in Zimbabwe include lack of capital, absence of digital infrastructure, resource immobility, conflicting interests in management, unavailability of necessary talent and skills, data security concerns, lack of integration and poor standardisation, among other factors. The need for more capital resources has hampered the Zimbabwean mining sector. PwC (2017) states that a lack of capital resources is also a barrier to the implementation of 4IR technologies. It is also expensive to procure and implement state-of-the-art 4IR technologies and infrastructures since technologies like automation are highly capital-intensive (Chilunjika & Chilunjika, 2024; Haurovi & Chilunjika, 2024). Installing technologies from the Fourth Industrial Revolution (4IR) in Zimbabwean mines does require a significant initial expenditure. It can cost hundreds of thousands to millions of dollars to install a complete network of sensors throughout a mine to monitor the equipment, the surrounding environment, and worker safety. Automated drilling and blasting equipment can run into several million-dollar ranges depending on its complexity and capabilities. Millions of dollars can be spent on autonomous haulage systems, robotic loaders, and drilling robots.

Most mines in Zimbabwe are located in remote areas, and the development of digital infrastructure still needs to catch up and catch up. The connectivity of mines in Zimbabwe is still low, and those connected do not support the industrial IoT. In light of this, 4IR technologies strongly depend on reliable internet connectivity, including data analytics, AI, and IoT devices. Installing and maintaining these technologies in places with spotty or inconsistent internet access is difficult. Additionally, there is a need for reliable transport networks and infrastructure. The adoption and timely support of 4IR technologies can be impeded by inadequate road networks and transportation

infrastructure (Chilunjika & Chilunjika, 2023; Zhou & Chilunjika, 2013; Chilunjika & Chilunjika, 2024). As such, the delivery and upkeep of sophisticated equipment depend heavily on efficient transportation. Similarly, a significant financial commitment is needed to build the infrastructure to support 4IR technology. Obtaining the money required for such development can be challenging in a nation facing economic difficulties, which slows the uptake of new technology (Chilunjika, Chilunjika & Uwizeyimana, 2024; Chilunjika, Chilunjika & Uwizeyimana, 2023).

Additionally, a more skilled workforce is needed to operate digital technologies. In this scenario, Hurovi and Chilunjika (2024) state that the absence of a workforce with requisite skills is one of the significant difficulties in executing Industry 4.0. Workforce expertise in data analytics, engineering, and IT is necessary to use 4IR technologies in mines effectively. Advanced technology adoption and operationalisation become easier with sufficient educational and training resources to produce such a workforce. To maximise the utilisation of 4IR technologies, skilled workers are required (Intauno, Chilunjika & Poshai, 2024; Chilunjika, 2024; Chilunjika, Intauno & Chilunjika, 2022). Mining operations only fully use the advantages of these technologies if the required skills are there, which could lead to less productive and subpar performance. Automation, machine learning, artificial intelligence, and advanced data analytics are examples of 4IR technologies that call for a workforce with specialised technical capabilities. It becomes easier for mining businesses to properly run and maintain these sophisticated 4IR equipment and machinery with the necessary training and experience. Insufficient expertise may result in inappropriate application or mishandling of cutting-edge technologies, leading to operations disruptions, equipment harm, or potential safety risks.

Furthermore, a shortage of more qualified personnel makes it more difficult for mining companies to train current employees and recruit new ones, which slows down the implementation process. To install and maintain 4IR technologies, mining companies frequently have to rely on foreign professionals due to a need for more local capabilities. According to Mpofo and Nemashakwe (2023), dependency on outside expertise may result in increased expenses and delays, as well as possible problems with knowledge transfer and the long-term viability of operations.

According to the 2016 Ministry of Mines Zimbabwe Report, the most significant barrier to conducting business in Zimbabwe is obtaining finance. This is because there are few options for offshore lines of credit (because of the high country risk profile), insufficient local funding, short-term funding, and extremely high interest rates. The Zimbabwean economy was subject to exchange rate volatility for most of 2022 (Chamber of Mines of Zimbabwe Report, 2022). During the time under consideration, the official currency rate experienced a cumulative depreciation of 493%, whilst the parallel market exchange rate declined by 296% during the same period. Concurrently, the premium on the parallel market decreased from 104% in January to 36% at the end of the year. The money supply expanded quickly in 2022, which put tremendous pressure on the exchange rate market due to inflationary forces in the economy. Half of the exporter miners' profit is retained in foreign exchange, with the remaining portion being paid in local currency (RTGS Dollars) at the current interbank market rate. Much of the forex is on the parallel market, where rates are several times more than the official (or interbank) market rates. This results in the failure to procure and invest in 4IR technologies since most of the technologies and equipment require hard currency to be procured. Additionally, it is difficult for mining companies to finance their day-to-day operational costs in this volatile economic environment.

The economy felt similar inflation pressures in the first half of 2022 due to rapid exchange rate depreciation and rapid expansion of the money supply. Month-over-month inflation rose from 2.7% in January 2022 to a peak of 18% in June 2022 (Zimbabwe Chamber of Mines Report, 2022). Month-over-month inflation fell from a peak of 18% in June 2022 to about 1.3% in December 2022 due to the government's strict liquidity management policies, which were implemented in the middle of the year. Inflation declined from 249% to 105.5% at the end of the year. All these economic dynamics, such as inflation, money supply and exchange rate volatility, make it difficult for

solid investment in 4IR technologies to be made in Zimbabwe's mining sector. The economic climate could be more conducive and stable for such investments.

Zimbabwe's mining industry needs more technological and infrastructural support. Chipangura (2018) states that small-scale, artisanal miners dominate the mining industry in Zimbabwe. The technology tools for mining extraction are severely lacking, and there are not enough innovative technical approaches to identify mining or mineral districts so that deeper drilling can be prioritised. In Zimbabwe, mining is highly labour-intensive and slow due to using hand tools. Furthermore, a significant issue in the mining industry is the need for more information and logistical infrastructure for collecting, storing, and distributing outputs (Chamber of Mines of Zimbabwe, 2018). This makes it difficult to convince and educate miners, let alone artisanal miners, about the benefits of 4IR technologies in their mining operations since there is no supporting infrastructure and technologies for the adoption and operationalisation of 4IR technologies across the mining sector in Zimbabwe.

The severe power shortages being experienced in the country have also affected the mining sector. The peak of electricity demand is 2,400MW, and generation has decreased to about 1120MW (Chaumba, 2017). The mining and industrial sectors are the country's primary energy consumers (Chikande, 2022). A mine, on average, requires uninterrupted power for at least 16 hours to ensure that production levels are maintained and that machines run optimally (Chipangura, 2018; Dube, 2016; Chamber of Mines of Zimbabwe, 2015). The Chamber of Mines of Zimbabwe (2015) estimates that a mining company may lose up to 6% of its revenue due to power interruptions. Electricity and electrical equipment are the primary power sources for most 4IR technologies, and obtaining, implementing, and operationalising these technologies in Zimbabwe's mining industry has become highly challenging. Above and beyond, a crucial component of the 4IR and a crucial point of entry for interconnection is digital infrastructure. In order to reap the benefits of the digital era, an internet connection is an essential requirement. Thus, its absence is the first barrier to digital inclusion.

Accordingly, security threats and breaches are also common, where mining systems are at risk of cybercrimes, hacking, and phishing, among other threats. Kovacs (2017), observed that the variety in the innovation basket implied that cybercrime and theft of private data and information might increase. Cybersecurity is necessary due to several significant cyberattacks, such as: application service attacks, in which the computer system's software applications are compromised, causing them to malfunction; web interface attacks, in which the attacker gains access to the web interface by using weak or insecure authentication protocols, compromising device integrity and potentially causing a denial of service; network attacks, which disrupt device communications, causing delays or message loss; and data integrity attacks, which entail manipulating stored or transmitted data (Poshai, Chilunjika & Intauno, 2023).

Additional dangers include defacing websites, phishing, virus and malware attacks, unauthorised access to data sources, data alteration and destruction, and other malevolent behaviours by attackers (Poshai et al., 2023; Joshi & Tiwari, 2012). These attacks can vary in intensity depending on how well the current cyber security measures work.

Additionally, the absence of feasibility studies to confirm the benefits of adopting 4IR technologies in the Zimbabwean mining sector is also a disincentive which has hampered solid investments in 4IR technologies in the mining sector. To this effect, it can be noted that many companies still need to carry out 4IR adoption feasibility studies and business case analyses that can justify implementation based on return on capital invested amongst capital expenditure appraisal methods (PwC, 2017; Schwab, 2016). This poses an additional constraint to the implementation of the 4IR. The same deductions were made by Deloitte (2018) who states that many organisations need clarification about the advantages of using 4IR technologies.

Conclusions and recommendations

Mining businesses in Zimbabwe have been gradually implementing 4IR technologies, which have gained traction in the last ten years. These technologies' productivity, safety, and operational efficiency have greatly increased. These businesses have managed to improve their overall performance, cut expenses, and optimise their processes using automation, artificial intelligence, the Internet of Things, and cutting-edge software. The study concludes that higher production, better mining safety performance, and lower production costs are ways the Internet of Things benefits the mining industry's performance. Analogously, through lowering production costs, raising productivity, and improving safety performance, automation of the mining value chain operations has a favourable effect on mining business performance. Through data-supported, data-driven decision-making for ongoing process improvement, big data analytics adds value to the company and lowers operating costs while increasing productivity. The mining businesses in Zimbabwe are experiencing higher productivity, cost savings, improved safety, and increased efficiency due to using 4IR technologies. Adopting 4IR technologies in Zimbabwe's mining sector has enabled mining operations to be more productive and efficient thanks to automation, which also decreases downtime. Additionally, by reducing exposure to dangerous surroundings, automation and remote activities have improved worker safety. Predictive maintenance has also assisted in lowering repair costs by foreseeing equipment faults.

Even with this, the successful deployment of 4IR technologies in Zimbabwe's mining sector is hindered by a number of factors, including capital limits, resource immobility, a lack of digital infrastructure, and a need for more expertise and skills. In dealing with the identified challenges, the following measures can be adopted:

- Educating stakeholders about the advantages and possibilities of 4IR technologies in the mining industry is also necessary through awareness-raising efforts. Mining companies should also involve all relevant parties in talks regarding technology adoption to guarantee support and address concerns, such as workers, communities, and government organisations.
- The development of Industry 4.0 should be directly overseen by the Ministries of Mines and Mining Development, ICT and Cyber Security through the allocation of funds to focus research agendas on ICT, IoT development, big data applications, and different technologies. Investments in stable and robust internet access are necessary for mining companies to enable the use of IoT devices and cloud-based software. This is especially important in distant mining areas where bandwidth is limited.
- There is a need to enact and fortify the legal and policy frameworks for supporting the implementation of 4IR in Zimbabwe's mining sector; investing in infrastructure, benchmarking, leapfrogging technology, research, and corporate-level innovation strategies are the most commonly suggested success factors for implementing the 4IR. The Zimbabwean government must establish and enforce laws that encourage using 4IR technologies. This covers tax breaks, financial aid for technology purchases, and more straightforward rules for the use of technology. Similarly, clear data protection and cyber security legislation must also be established to guarantee the security and privacy of data gathered via 4IR technologies. The government should assist in streamlining regulatory procedures to facilitate mining businesses' adoption and integration of new technology. Safety and interoperability should be guaranteed in the mining industry by creating and using standards and guidelines for 4IR technologies.
- Programs for mine personnel to acquire the skills required to operate and maintain 4IR technologies must be developed and put into place. Universities and technical institutes can collaborate to do this. Comparably, through certification programs and workshops centred on the most recent developments in mining technologies, mining businesses must promote ongoing learning and upskilling.
- Governmental organisations, projects, and programs must strive towards luring capital, establishing partnerships, cooperation, and strategic communication with overseas companies acknowledged for their leadership in Industry 4.0. This will facilitate the spread, acquisition, and transfer of technology to benefit domestic businesses. Mining businesses and technology suppliers must form partnerships to promote

knowledge and technology transfer. Thus, public-private partnerships must be established to share the risks and rewards of technology adoption programs and co-fund them (Chilunjika, 2024; Tapia, 2020). Additionally, mining companies should have a corporate strategy on innovation, invest in digital infrastructure, and benchmark with other companies that have successfully implemented these technologies.

- It is necessary to give mining businesses access to reasonably priced financing options so that they may invest in 4IR technologies. Grants, loans, and collaborations with government-supported financial institutions can accomplish this. As part of this, mining businesses that invest in new technology may also be eligible for tax cuts and other financial advantages.
- By giving grants and financing to universities and research organisations, it is essential to promote research and development in mining technology. To encourage creativity and the creation of locally applicable solutions in light of this, it is also necessary to set up innovation hubs and technological incubators centred on the mining industry. Moving on, vocational training and higher education programs can be tailor-made to suit related competencies and skills that are compliant with the 4IR technologies, with long-lasting benefits for employability and the functioning of education systems.
- Installing contemporary cyber security technology, such as firewalls, Internet gateways, and virus protection software, is necessary to monitor and promptly report mining sector-related cyber security incidents before they impact individuals or mining organisations. These defences can safeguard mining institutions and citizens from the dangers of being online and using internet-operated equipment. By using such cyber protection technologies, mining institutions can also increase the integrity and security of their data.

Stakeholder involvement, infrastructure development, policy enactment and regulatory support, innovation and research, capacity building and training, and financial assistance are all essential components of a holistic strategy to increase the uptake of 4IR technologies in Zimbabwe's mining industry. The Zimbabwean mining sector may gain a competitive edge in the global market by implementing these recommendations and improving the productivity, efficiency, and sustainability of its mining activities.

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ISSN 2669-0195 (online) <https://jssidoi.org/ird/>

2024 Volume 6 Number 4 (December)

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Funding: There was no funding for the conducting of this research, but the School of Public Management, Governance and Public Policy at the University of Johannesburg was responsible for paying the article processing charges.

Data Availability: The author does agree that all the data and materials supporting this work is accessible and can be available at any given time upon request. The authors may avail the data via emails or from official websites and portals of the concerned institutions.

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