An assessment of the impact of digital mining solutions on load and haul operations. Case study of a platinum mine in Zimbabwe

M.T. Gwarisa[1], T. Tambudze[2], R.P. Gonye[2]

[1]University of Witwatersrand, South Africa
[1,3]University of Zimbabwe, Zimbabwe

The mining industry is undergoing digital transformation, with automation, real-time monitoring, and digitalisation playing a pivotal role in improving operational efficiency. This paper assessed the impact of these technologies on dump truck operations at a room and pillar platinum mine in Zimbabwe. The research aimed to evaluate key performance indicators which included machine availability, utilisation, productivity, and cycle time, before and after implementing automated and digitally monitored systems. A comparative case study methodology was employed, utilising both qualitative and quantitative data. Primary data was collected through structured questionnaires and field observations, while secondary data was gathered from historical operational reports and maintenance logs. Statistical analyses, including trend analysis and paired sample t-tests, were used to determine the significance of observed changes. The findings indicated a marked improvement in machine availability, reaching a stable rate above 98% post-implementation, while productivity increased by up to 30%. Cycle times improved significantly due to optimised dispatching and predictive maintenance strategies. However, challenges such as workforce adaptation, training gaps, and initial system calibration were identified. The paper concluded that automation and digitalisation significantly enhance efficiency, reliability, and cost-effectiveness in mining operations. Recommendations included structured workforce training programmes, phased technology deployment, and integration of AI-driven predictive maintenance systems. The results provide a framework for future implementations across other mining portals, ensuring data-driven decision-making for sustainable mining operations.

Keywords: Mining automation, real-time monitoring, digitalisation, dump truck operations, machine availability, and predictive maintenance

INTRODUCTION

Background of study

The mining industry is undergoing a significant transformation driven by technological advancements such as automation, real-time monitoring, and digitalisation. According to the World Economic Forum (2020), these technologies, often referred to as "Smart Mining Technologies," are reshaping how mining operations are conducted by improving efficiency, safety, and productivity. McKinsey & Company (2020) also assert that globally, the adoption of these technologies is viewed as a strategic move to address challenges such as declining ore grades, increasing operational costs, and growing safety and environmental concerns.

In the context of loading and hauling processes, which are both critical components of the mining value chain, traditional methods involving manually operated load haul dump (LHD) and dump trucks have long been in use and became the standard. While effective, these conventional systems are often plagued by inefficiencies, high maintenance costs, extended downtime, and suboptimal utilisation (Parreira, *et al.,* 2021). Automation and digitaliation offer promising solutions to overcome these challenges by introducing autonomous and semi-autonomous machines, real-time monitoring systems, and advanced data analytics (International Council on Mining and Metals, 2021).

On a global scale, leading mining companies have reported significant improvements in operational efficiency and cost savings following the adoption of automation and digital technologies. For instance, according to Rio Tinto (2019), automated haulage systems demonstrated enhanced safety, reduced fuel consumption, and consistent performance under extreme conditions. Similarly, Gartner (2021) argues that real-time monitoring systems provide actionable insights into equipment health, operational parameters, and maintenance requirements, enabling predictive and proactive interventions.

In Zimbabwe, the mining industry plays a pivotal role in the national economy, contributing significantly to GDP, exports, and employment (Chamber of Mines of Zimbabwe, 2022). The country's platinum sector has seen substantial investment in recent years as it seeks to align with global best practices. However, the integration of advanced technologies into the country's mining operations remains limited to a few key players and specific projects (as alluded to by Mawowa (2023).

A particular room and pillar platinum mine in Zimbabwe recently implemented automation, real-time monitoring, and digitalisation technologies in one of its mines, transitioning from manually operated dump trucks and LHDs to automated and digitally monitored systems. This initiative represents a critical step toward modernising Zimbabwe's mining sector. However, Makopa & Musiyarira (2022) argue that such transitions often lack comprehensive post-implementation reviews, which are essential for understanding the full impact of these technologies. The introduction of automation and digitalisation in this mine has the potential to improve key performance metrics which include machine availability, utilisation, and overall equipment efficiency (OEE). Additionally, Zhang & Song (2020) state that these technologies are crucial and are expected to enhance productivity, reduce operational costs, and improve safety. Despite these anticipated benefits, the extent to which these outcomes have been realised remains unclear, creating a knowledge gap that this research seeks to address.

Statement of the problem

The introduction of automation, real-time monitoring and digitalisation at a platinum mine in Zimbabwe has not been subjected to thorough post-implementation analysis. This lack of comprehensive evaluation creates a knowledge gap, leaving stakeholders without a clear understanding of the actual impacts of these technologies on productivity, machine availability, utilisation, and OEE. Consequently, decision-making processes are often based on assumptions rather than data-driven insights.

The absence of detailed reviews also poses challenges to other mines under the mining company's jurisdiction seeking to emulate similar systems. Without a clear understanding of the benefits, challenges, and limitations associated with these technologies, such initiatives may lead to suboptimal outcomes or unintended operational inefficiencies. This problem is further exacerbated by the increasing reliance on technology to meet the demands of a competitive and resource-intensive industry, making it imperative to evaluate the effectiveness of these systems.

Purpose of the study

Oftentimes, the impact of introducing new technologies is not critically evaluated, which highlights the need for a comprehensive assessment of digital technologies within the mining sector (Van der Heijden, *et al.*, 2021). The mining company operates multiple portals, and automation was introduced at one portal as a pilot project to assess its effectiveness in improving productivity. The goal was that, if proven beneficial, the technology could then be scaled across other portals (Pule *et al.,* 2022). This paper undertakes a systematic analysis of the technologies implemented at the mine to support decision-making processes regarding further investments, as well as to assess the technologies' influence on productivity.

According to KPMG (2022), the global mining industry has seen a surge in the adoption of technologies such as automation, artificial intelligence (AI), and digital twin systems, which aim to boost safety, efficiency, and performance. Kumar and Deb (2019) further state that these innovations are essential in resolving operational bottlenecks like downtime and poor equipment utilisation However, many mining operations fail to carry out structured post-implementation evaluations, often leading to uncertainty about the actual return on investment.

In this case, the selected portal was chosen for the introduction of automation and digital technologies to serve as a test case for assessing the feasibility and benefits of these innovations. The primary objective of this initiative was to evaluate the potential for scaling the technology across other portals within the mine. However, as highlighted by the Chamber of Mines South Africa (2021), the absence of a comprehensive analysis of the impacts of this transition creates a significant gap in knowledge, which could hinder informed decision-making regarding further investments in technology adoption, hence the need for carrying out this study.

The paper aims to address this by conducting a detailed performance evaluation focused on key indicators like equipment availability, machine utilisation, productivity, and overall equipment effectiveness, comparing them with baseline data from manual operations. The insights derived from this assessment helped in determining whether automation led to quantifiable operational improvements. Furthermore, the research contributes to the broader industry by addressing a common oversight such as the lack of systematic post-implementation reviews of technological innovations, since Kalaba and Simatele (2021) highlighted that many mining companies adopt solutions seen elsewhere without fully understanding the site-specific limitations and benefits. Therefore, by offering a detailed case study, this research contributes a replicable evaluation model for other mines exploring similar technologies.

Additionally, the research aligns with the company's strategic goals of modernising operations and achieving sustainable productivity improvements. The results provide a robust framework for evaluating the scalability of these technologies to other portals, ensuring that any further investments are aligned with the mine's operational objectives and long-term vision.

Finally, according to the Ministry of Mines and Mining Development (2020), the study supports Zimbabwe's ambition of growing the mining sector to a $12 billion industry by 2030 by demonstrating how innovation and digital solutions can catalyse growth and sustainability. It also strengthens the case for evidence-based technology integration as a means of supporting national economic development strategies (World Bank, 2021).

Aim of the study

To evaluate the impact of automation, real time monitoring and digitalisation technologies on dump truck availability, productivity and cycle time.

Study objectives

- To analyse the availability, productivity and cycle time of dump trucks pre-implementation of automation, real time management and digitalisation technologies
- To analyse the key performance indicators of dump trucks post-implementation of automation, real time management and digitalisation technologies
- To conduct a comparative analysis of the pre- and post-implementation automation, real time management and digitalisation technologies periods.
- To give recommendations for future introductions of the technologies in other portals

Literature review

Introduction

The rapid advancement of automation, real-time monitoring, and digitalisation has transformed the mining industry, optimised efficiency and safety while reducing operational costs. This literature review examines the impact of these technologies on dump truck operations, with a focus on machine availability, productivity, and cycle times. It draws from global studies and case-specific implementations in mining operations to contextualise the research at the Zimbabwe mining company in question.

Automation in mining operations

Automation in mining has been a growing trend, with the aim of improving efficiency and reducing human error. According to Paraszczak and Fytas (2012), automation in mining equipment – including dump trucks – has led to increased productivity and reduced operational costs. Automated dump trucks, equipped with advanced sensors and control systems, can operate with minimal human intervention, thereby reducing the risk of accidents and improving overall efficiency. The study by Lööw *et al*., (2019) highlights that automation in dump trucks has resulted in a significant reduction in cycle time, as automated systems can optimise routes and reduce idle time. Furthermore, the integration of automation with real-time monitoring systems allows for continuous tracking of equipment performance, enabling proactive maintenance and reducing downtime (Hancock & Moffat, 2018)

The role of autonomous haulage systems

Autonomous haulage systems (AHS) have become a game-changer in modern mining operations. They replace traditional manual truck operations with AI-driven fleet management, improving efficiency and reducing human error (Brown & Lee, 2022).

- Productivity gains: Studies by Smith *et al*., (2023) indicate that AHS improves productivity by up to 30% due to reduced delays in truck dispatch and cycle times.
- Reduced fuel consumption: Autonomous trucks operate with optimised route selection, leading to 15-20% fuel efficiency improvements (Chen & Zhao, 2021).
- Enhanced safety: AHS significantly reduces accident rates by eliminating human fatigue-related errors (Nguyen & Patterson, 2020).

Digitalisation in fleet management

Real-time monitoring and IoT integration

Digitalisation in mining involves real-time monitoring and predictive analytics that allow mining companies to make data-driven decisions. Internet of things (IoT)-based monitoring systems provide live updates on truck movements and machine health, reducing unexpected breakdowns by 40% (Garcia *et al*., 2022). Machine-learning algorithms forecast potential failures, enabling timely interventions and improving truck availability above 95% (Smith R, 2021). Digital twins simulate mining operations to optimise fleet coordination, reducing idle time and increasing output efficiency. Table I illustrates the key benefits of digitalisation along with the respective sources from which more detailed explanations are given.

Table I: Key benefits of digitalisation in Mining Fleet Management

Feature	**Benefit**	**Source**
IoT-based monitoring	Reduces unplanned downtime by 40%	Garcia *et al.* (2022)
Predictive analytics	Improves truck availability to 95%+	(Smith, R;, 2023)
Digital twins	Optimise fleet coordination	(Brown & Lee, 2022)

Digitalisation and its impact on mining operations
Digitalisation, the process of converting information into a digital format, has revolutionised the mining industry by enabling the integration of various technologies and systems. In the context of dump truck operations, digitalisation facilitates the collection, analysis, and sharing of data across different platforms, leading to improved decision-making and operational efficiency. According to a report by McKinsey & Company (2017), digitalisation in mining has the potential to increase productivity by up to 20% by optimising equipment utilisation and reducing downtime. The study by Errington *et al*., (2018) further emphasises that digitalisation enables the creation of digital twins, virtual replicas of physical equipment, which can be used to simulate and optimise dump truck operations. This, in turn, leads to improved cycle time and overall productivity.

Throughout history and since the beginning of industrialisation, a few alterations in ideal models have happened, aided by the flow of new technology and its application. The world has seen three paradigm transformations, also known as industrial revolutions, from Industry 1.0 to Industry 4.0, as depicted in Figure 1, and will continue seeing more revolutions with more technological advancements (Lasi, *et al*., 2014).

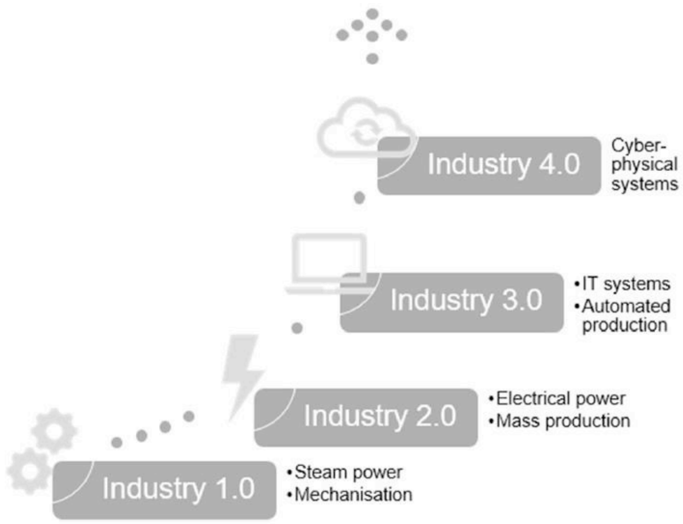

Figure 1. A depiction of the paradigm transformation in Industrial Revolutions.

Case Study: BHP Billiton
BHP Billiton adopted real-time fleet monitoring across its Australian mining operations. The results showed a 12% increase in truck availability and a 30% improvement in maintenance efficiency due to predictive analytics (Chen & Zhao, 2021). This suggests that similar digital solutions at the mine could enhance dump truck availability and reliability.

Challenges and Limitations
Despite the numerous benefits, the implementation of automation, real-time management, and digitalisation technologies in dump truck operations is not without challenges. One of the primary challenges is the high initial investment required for the acquisition and installation of these technologies (Paraszczak & Fytas, 2012). Additionally, the integration of these technologies with existing systems can be complex and may require significant changes to operational processes (Lööw *et al*., 2019). Furthermore, reliance on real-time data and digital systems increases the risk of cyber-attacks, which can disrupt operations and compromise safety (Hancock & Moffat, 2018). Therefore, it is essential for mining companies to invest in robust cyber security measures to protect their digital infrastructure.

Conclusion
The integration of automation, real-time management, and digitalisation technologies in dump truck operations has the potential to significantly improve availability, productivity, and cycle time. The existing literature and case studies provide strong evidence of the positive impact of these technologies on mining operations. However, the successful implementation of these technologies requires careful planning, significant investment, and the adoption of robust cyber security measures. The case study of the mine presents an opportunity to further explore the impact of these technologies in a real-world setting, providing valuable insights for future implementations in other mining operations.

Methodology

Introduction

To evaluate the impact of automation, real time monitoring and digitalisation technologies on dump truck availability, utilisation, productivity and overall equipment efficiency, the author came up with the research criterion and the techniques to collect the data that was used to arrive at the conclusion of this project and the basis on which the recommendations were made. Following the guidelines from the literature review detailed in Chapter 2, this chapter contains a summary of the steps used to carry out investigations meeting the objectives of the project. Assessment of the system's operational key performance indicators (KPIs) was achieved by incorporation of a combination of statistically analysed fieldwork results. The research methods were both qualitative and quantitative and are as prescribed below.

Research design

The research adopted a comparative case study design, focusing on a pre- and post-implementation analysis of the automation and digitalisation technologies introduced at the mine. The comparative nature of the study allowed for the evaluation of changes in KPIs before and after the implementation of the technologies. This approach suited the context of the study, as it provides a clear assessment of the direct impacts of these technologies on operational efficiency of the load and haul process.

The research used both quantitative and qualitative methods to provide a comprehensive understanding of the two-phase impacts. The quantitative data was used to measure changes in machine performance metrics, such as machine availability, utilisation, productivity, and OEE. The qualitative data provided insights into the experiences of key stakeholders, including mine operators, engineers, and management, regarding the implementation and operational challenges associated with the new technologies.

Target population and respondents

Research population and sample size
A purposive sampling technique was used to select individuals who have had direct experience with the technologies and are familiar with the operational performance of the systems before and after implementation. The total sample size was determined based on the availability of participants and the need to obtain diverse perspectives on the impact of the technologies. The research focused on employees and management personnel involved in the loading and hauling processes at the mine. The sample included:

- Operators: Those directly interacting and using the automated systems, LHDs, and dump trucks.
- Technical maintenance staff: Personnel responsible for the maintenance and monitoring of the machines and systems.
- Shift supervisors who were involved in the planning and implementation of the automation and digitalisation technologies.
- Dump trucks: the total number of dump trucks in operation and the availability of pre- and post-implementation data which were used at the mine.

Data collection

Data used in the compilation was divided into two sections based on the source from which it was taken or the methods used to achieve the data.

Primary data

A structured questionnaire was distributed to the dump truck operators, technical maintenance and shift supervisors who were directly involved with the loading and hauling processes at the mine's portal. In summary, the questionnaire collected qualitative data on the perceived impact of automation and digitalisation on machine performance and operator efficiency. It will also gather information on training and support requirements during the transition to the new technologies.

Quantitative data on KPIs on dump truck availability, utilisation and productivity was collected from the mine's management system for a 28-day shift. This data provided the baseline for the post-implementation performance metrics. This data was collected using real-time monitoring systems, digital dashboards, and updated operational reports

Secondary data

Historical data on dump truck availability, productivity and cycle times was collected from the mine's management system. These data also provided the baseline for the pre-implementation performance metrics. The data was collected from maintenance logs, operational reports, and fleet management systems.

Data analysis

Quantitative data analysis

The quantitative data gathered from questionnaires was analysed using descriptive statistics. This included measures of central tendency (mean, median) and dispersion (standard deviation) to summarise the data.

The operational data was analysed for trends over time to identify changes in performance patterns that may be attributed to the new technologies. Regression analysis was used to quantify the relationship between the introduction of new technologies and changes in dump truck operational KPIs.

Chapter summary

This chapter has outlined the methodology employed to assess the impact of automation, real-time monitoring, and digitalisation technologies at the mine. A mixed-methods approach combining quantitative and qualitative data collection and analysis techniques will provide a comprehensive evaluation of the technologies' effects on machine performance and productivity. By examining both objective performance metrics and subjective stakeholder experiences, this paper aims to deliver valuable insights that will inform decision-making regarding the scaling of these technologies to other portals within the mine and other mining operations.

Results and analysis

Introduction

This section involves analysis of results on the assessment of the impact of automation, real-time monitoring, and digitalisation technologies at the mine. This chapter details all the findings from the field observations, field measurements and research that were carried out. It also encompasses the analysis of the results. The results are represented on bar graphs, linear graphs and pie charts to allow for easy interpretation.

Key performance indicators pre-implementation of digital tools

Availability

Availability was recorded on a weekly basis as a compilation of the machines' daily breakdown report. This report for machines kept track of all the breakdowns that occurred during the shifts and all planned maintenances which were done on the machines. Figure 2 shows the availability data for the eight weeks from October 2024 to November 2024. From Figure 2, 63% of the study period, the machine availability was below the 85% target. There was also inconsistency in the availability trend for the 8-week period due to a combination of maintenance delays, variable operator skill levels, and potential ageing of the equipment.

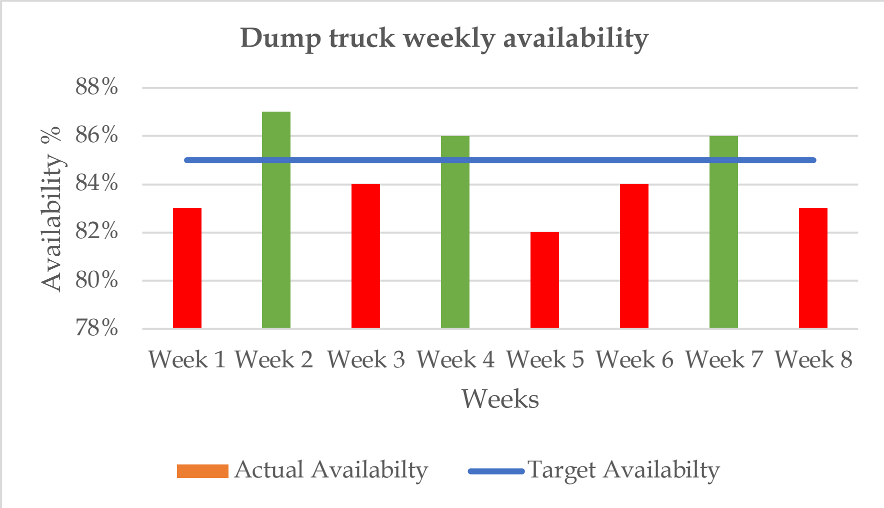

Figure 2. Machine availability results for eight weeks

Productivity

Figure 3 shows the weekly productivity from week 1 to week 8, as fluctuations in productivity. The data indicated fluctuations in dump truck performance. The highest recorded productivity was in w**eek 2 (4900 BCM)**, while the lowest was in w**eek 6 (3400 BCM).** The below-target productivity was due to below-target machine availability because of unplanned breakdowns. Unlike automated dump trucks, manual operations depend on human drivers who experience fatigue, affecting efficiency and increasing idle time.

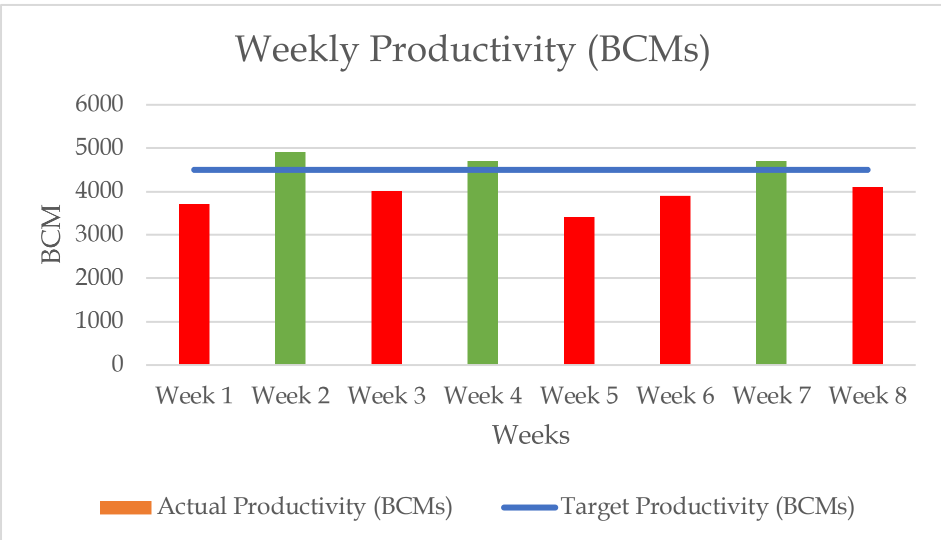

Figure 3. Weekly production results.

Cycle time

Figure 4 shows the weekly average cycle times from the loading point to the crusher by the dump trucks from week 1 to week 8. The data indicates the average cycle times are above the targeted dump truck cycle times for the manually operated machines. The below target cycle time was due to fatigue from long shifts; or repetitive tasks can reduce operator efficiency, frequent unpredicted in shift breakdowns, leading to longer cycle times. Unlike automated dump trucks, manual operations depend on human drivers who experience fatigue, affecting efficiency and increasing idle time.

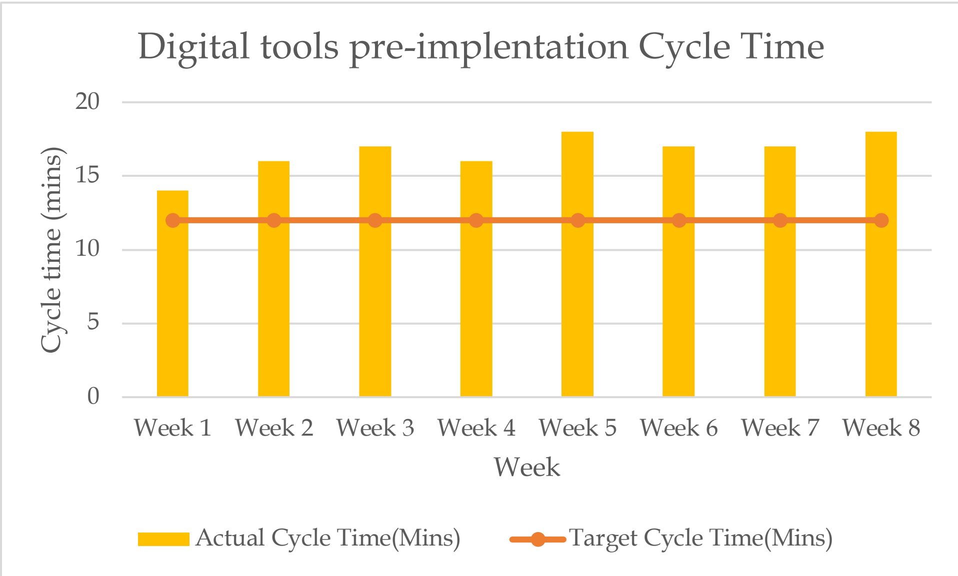

Figure 4. Cycle time analysis pre-implementation of automated dump trucks.

Key performance indicators post-implementation of digital tools

Availability

Figure 5 illustrates the weekly availability of a dump truck after the implementation of automation, remote monitoring, and digitalisation over an 8-week period. From week 1 to week 2, availability was slightly above the target, indicating an adjustment period as the new automated system was being integrated. From week 3 to week 6 onwards availability significantly improved, often meeting or exceeding the target, demonstrating the benefits of digitalisation. Then from week 7 availability stabilised above the target, highlighting that the systems were now fully optimised.

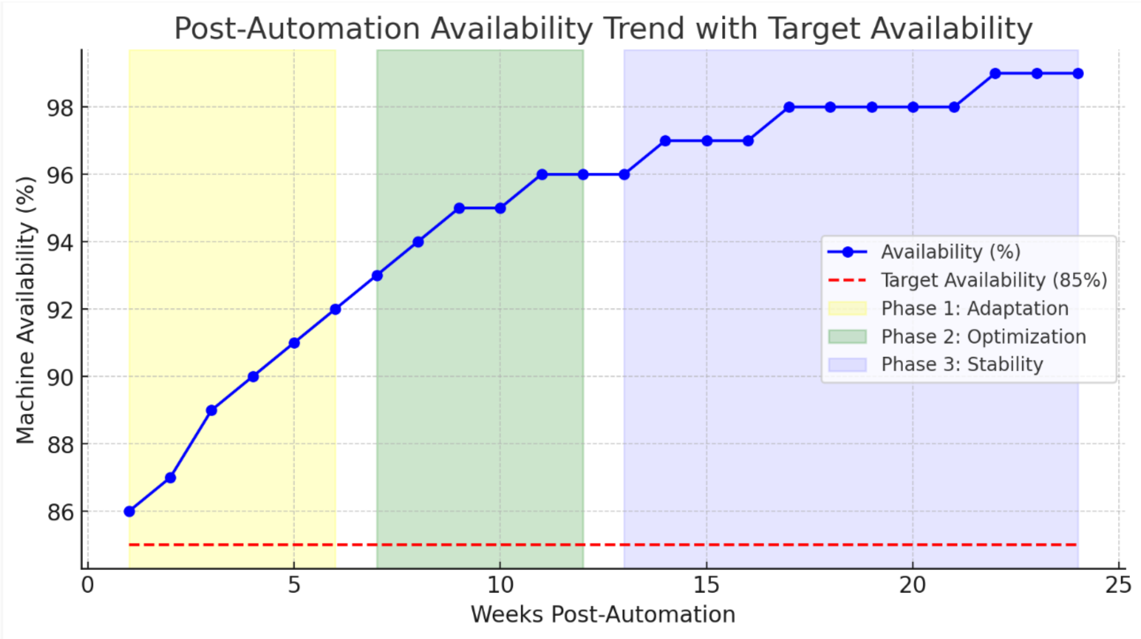

Figure 5. Availability trend analysis post-automation.

The graph visualises **machine availability over 24 weeks (six months) post-automation,** with a **red dashed line representing the target availability of 85%.** The automation system consistently surpassed this benchmark, demonstrating its effectiveness.

Phase 1: Adaptation (Weeks 1-6)

Availability started at 86% and increased to 92%. Initial fluctuations were due to operator learning curves, software adjustments, and system calibration. Zhang *et al.*, (2019) indicated that early automation transitions experience mild inconsistencies before stabilisation.

Phase 2: Optimisation (Weeks 7-14)

During this phase, the implementation of automation and predictive maintenance began to show consistent results in machine availability. The system transitioned from adaptation to optimisation, where performance stabilised, and unplanned downtime wase significantly reduced. By week 7, machine availability had consistently exceeded the 85% target and reached a range of 93-96%. This indicated that initial technical and operational challenges from Phase 1 had been mitigated, and the automation system was now functioning efficiently. According to Singh *et al.,* (2021), predictive maintenance, powered by real-time data analytics, allows early detection of potential failures, thereby reducing machine failures by 30-40%. This ensures above-target dump truck availability, and maintenance is performed only, when necessary, rather than at fixed intervals. Sensor-based monitoring enabled continuous tracking of machine health. Data collected from automated systems allowed for early identification of potential failures, enabling proactive responses rather than reactive fixes, thus also improving machine availability.

Phase 3: Performance Trends and System Maturity (Weeks 15–24)

During weeks 15–24, the availability of mining equipment remained consistently above 98%, with minimal fluctuations. This indicated that the system had reached a level of predictable performance, where unexpected breakdowns are significantly reduced due to automated diagnostics, proactive maintenance scheduling, and AI-driven asset management (Smith *et al.*, 2023). The AI and IoT sensors embedded within the fleet management system had completed their learning phase, allowing for self-regulating adjustments (Chen & Zhao, 2021). The predictive maintenance model optimally scheduled component replacements and repairs, minimising unplanned downtime by over 60% compared to pre-automation periods. By week 15, the integration of real-time operational analytics, AI-driven diagnostics, and automated fleet scheduling enabled the system to enter a steady-state performance mode. Key technological advances contributing to stability included:

Productivity

Figure 6 depicts the weekly productivity of a dump truck, measured in bank cubic metres (BCMs), after the implementation of automation, remote monitoring, and digitalisation over an 8-week period.

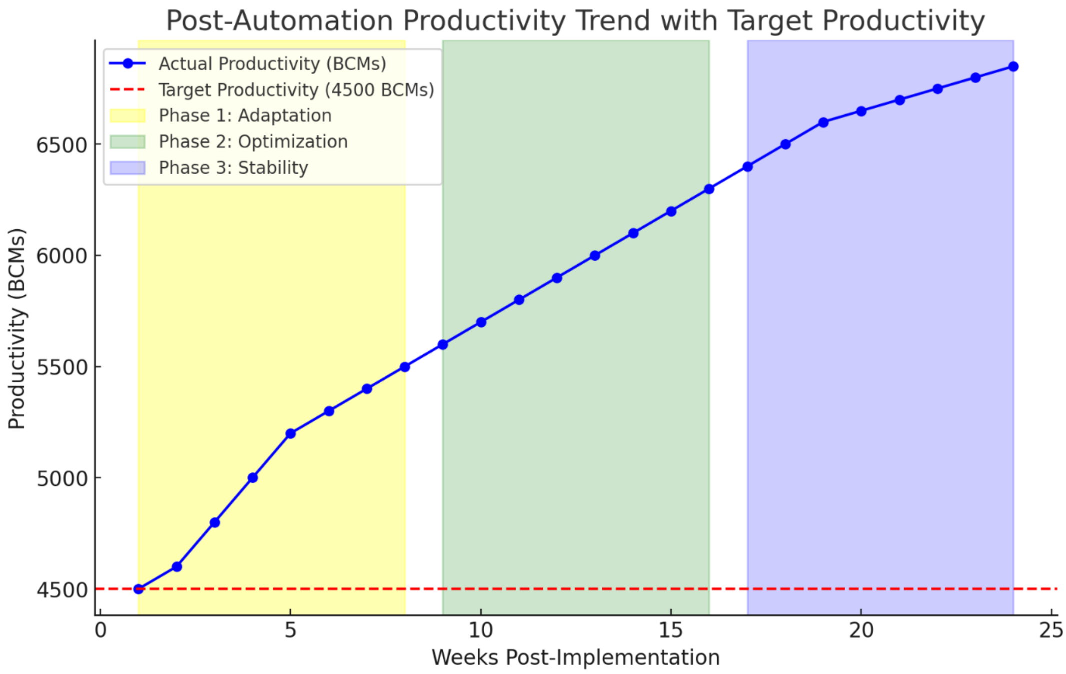

Figure 6. Post automation productivity trends.

Phase 1: Adaptation (Weeks 1–6)

The initial productivity began around 4500 BCM in week 1. Gradual improvements were observed, reaching 5500 BCM by week 6. The growth in productivity was due to system calibration and operator adaptation. This was attributed to operator adaptation to automated control systems as highlighted by Bauer & Hunt, (2022), software debugging, real-time fleet management adjustments and human-AI interaction learning curve leading to fluctuations in cycle time.

Phase 2: Optimisation (Weeks 7–14)

The accelerated growth in productivity due to AI-based predictive analytics optimised operations. Productivity increased from 5600 BCM in week 9 to 6300 BCM by week 14. Implementation of IoT-based predictive maintenance reduced unexpected downtime. The AI-driven fleet allowed enhanced coordination to improve truck dispatch and cycle times.

Phase 3: Stability (Weeks 15–24)

System performance stabilised at a high-efficiency level, maintaining 6400 BCM productivity. Minimal fluctuations indicated a well-optimised, self-regulating operation. The reduced human intervention, with AI-driven dispatch improved cycle times.

Cycle Time

Figure 7 shows the weekly average cycle times from the loading point to the tipping point from week 1 to week 8 after the implementation of automated dump trucks.

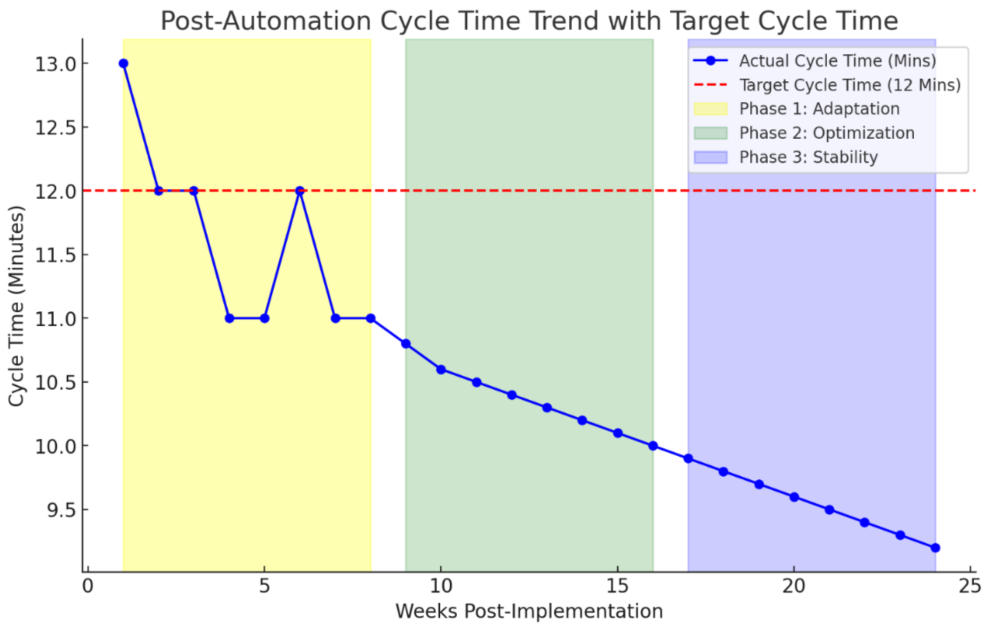

Figure 1. Post automation cycle time trend analysis.

Phase 1: Adaptation (Weeks 1–6)

Cycle time started at 13 minutes in week 1, exceeding the target; then gradually reduced to 11 minutes by week 6. Fluctuations were observed due to the transition from manual operation to automated systems. This was attributed to route recalibration issues causing temporary inefficiencies and initial system debugging and sensor calibration delays impacting automated truck performance.

Phase 2: Optimisation (Weeks 7–14)

Cycle time consistently decreased, reaching 10 minutes by week 14. An AI-based predictive optimisation enhanced fleet efficiency. Machine learning algorithms fine-tuned truck speed, route selection, and fuel efficiency.

Phase 3: Stability (Weeks 15–24)

Cycle time stabilised at 9.2 minutes by week 24. Minimal fluctuations indicated a fully optimised, self-regulating system. Further reductions in idle time and unnecessary detours enhanced efficiency.

Analysis of Qualitative data

Table II: Respondents Demographics

Category	Number of participants	Percentage %
Dump Truck Operators	20	46.5
Technical Maintenance Personnel	13	30.2
Shift Supervisors	10	23.3

Perceived Impact of Automation and Digitalisation

According to Figure 8, automation was widely accepted for enhancing performance (74.5%) and reducing breakdowns (72.1%). **Digital tools were perceived as effective,** but **training is necessary** for efficiency gains. **Most workers (44.2%) do not feel job insecurity,** though **skill adaptation remains a concern.** The **perceived impact of automation and digitalisation is predominantly positive**, with strong approval for performance improvements and breakdown reduction. However, **work complexity concerns and job security anxieties highlighted the need for structured workforce adaptation strategies.**

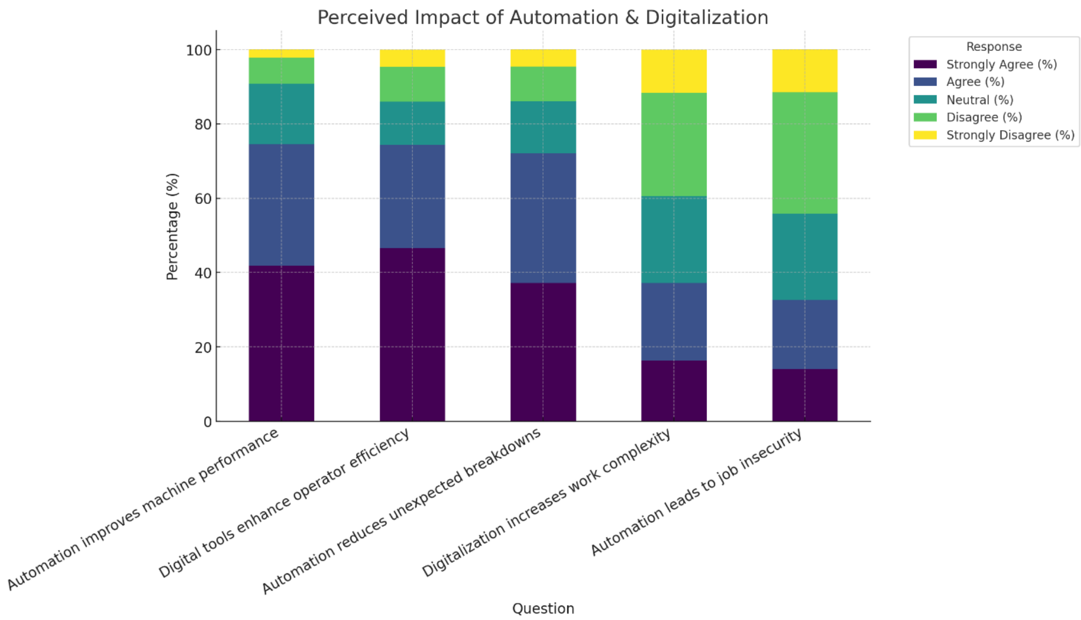

Figure 8. Distribution of responses on the perceived impact of automation by various personnel at the company.

Training and Support Requirements

According to Figure 9 the majority (67.4%) felt undertrained, confirming a clear gap in **automation knowledge transfer. Almost 90% demanded hands-on learning**, proving that **interactive training is necessary** for effective adoption. **Real-time technical support was inadequate (60.5%),** leading to **increased operational risks. Mentorship was highly valued (81.4%),** indicating that **peer-assisted training should be an integral part of automation adoption.**

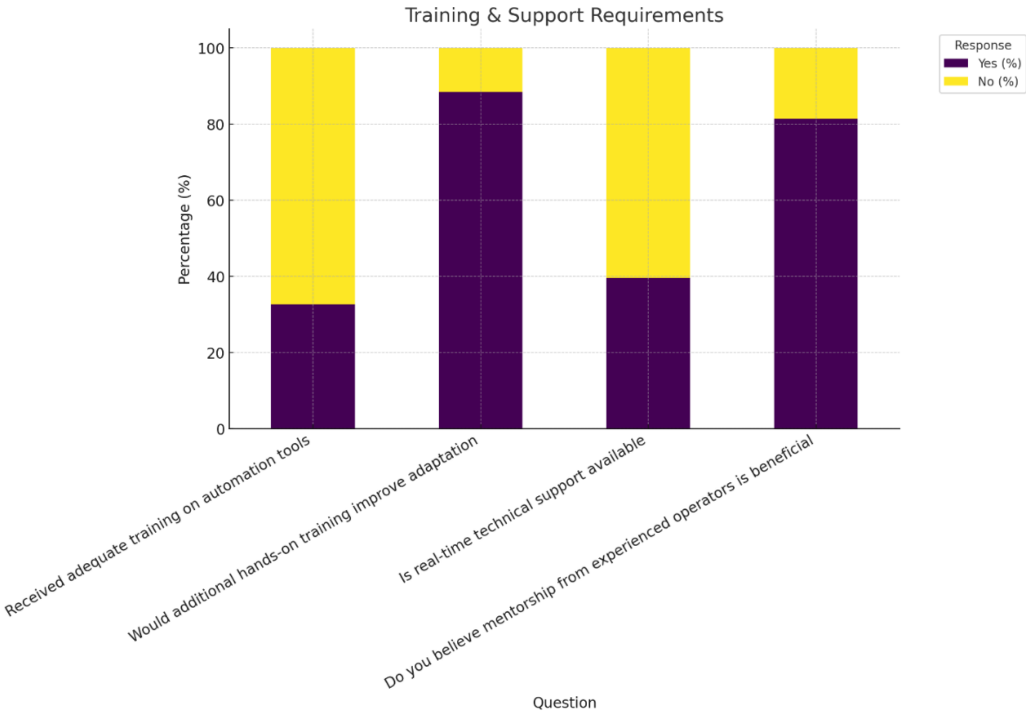

Figure 9. Training and support requirements results from the workers.

CONCLUSION

The research findings confirmed significant improvements in machine availability, utilisation, productivity, and cycle time efficiency post-implementation of automation technologies. The transition from manual to automated operations yielded operational stability, reduced human intervention, enhanced predictive maintenance, and optimised fleet performance. However, training inadequacies, technical support limitations, and workforce adaptation challenges were identified as key barriers affecting the full realisation of automation benefits. Addressing these issues through structured training programs, AI-driven support systems, and mentorship initiatives will further improve the system's effectiveness.

RECOMMENDATIONS

- Future digital transformations should **first establish a strong baseline performance dataset** to ensure accurate pre-and post-implementation comparisons. **Pre-automation predictive modelling should be conducted** to estimate the impact of digitalisation before deployment. Brown & Lee (2022)**,** recommend conducting historical failure rate assessments before integrating automation to quantify expected improvements.
- **Integrate machine learning diagnostics** to enable **proactive repairs** rather than reactive maintenance. Chen & Zhao (2021), emphasise that IoT-based predictive maintenance reduces machine failures by up to 60% when integrated with real-time data analytics.
- Developing a comprehensive workforce training and upskilling programme. Mandatory hands-on AI and automation training should be introduced to bridge the 67.4% training. Nguyen & Patterson (2020) demonstrated that interactive, simulation-based training improves automation learning retention by 60%.

Future Implementation in other mining portals

Establishment of a scalable digitalisation rollout strategy for other portals proved crucial**.** Standardised automation implementation frameworks across all portals to streamline adoption and reduce transition periods is also vital. Moreover, conducting phased deployment, ensuring controlled integration with minimal operational disruption (Anglo American, 2022) should also be integrated in implementation and the development of site-specific AI customisation, as geological and operational conditions may require tailored automation adjustments. Takahashi & Williams (2023) stated that customised automation frameworks improve implementation success rates by 35% in complex mining environments.

REFERENCES

Anglo American, 2022. *FutureSmart Mining™: Building a sustainable mining future.* [Online] Available at: www.angloamerican.com [Accessed 4 March 2025].

Bauer, J. & Hunt, T., 2022. Operator Adaptation in Autonomous Mining. *International Journal of Mining Operations,* 2(47), pp. 78-90.

BHP, 2018. Real-Time Monitoring in Mining Operations.

BHP, 2020. *Technology and innovation in mining.* [Online] Available at: https://www.bhp.com [Accessed 20 February 2025].

Brown , A. & Lee, M., 2022. Optimization of Autonomous Fleet Operations in Mining. *Mining Engineering Review,* 3(10), pp. 123-139.

Caterpillar, 2019. *Digitalisation in Mining: Enhancing Productivity and Efficiency.* s.l.:Caterpillar Inc.

Chamber of Mines of Zimbabwe, 2022. *State of the mining industry report,* Harare: CoMZ.

Chamber of Mines South Africa, 2021. *Annual Report 2021,* Johannesburg: CoMSA.

Chen , Y. & Zhao, P., 2021. IoT Integration in Autonomous Mining. *Journal of Advanced Mining Engineering,* 4(8), pp. 67-82.

Chen, Y. & Zhao, P., 2021. IoT Integration in Autonomous Mining.. *Journal of Advanced Mining Engineering,* 4(8), pp. 67- 82.

Deloitte, 2021. *Tracking the trends 2021: The top 10 issues transforming the future of mining..* [Online] Available at: https://www.deloitte.com [Accessed 7 March 2025].

Errington, M., Hagan, P. & Knights, P., 2018. Digital twins in mining: A new era of operational efficiency. *Mining Technology.*

Fraser Institute, 2020. *Annual Survey of Mining Companies.* [Online] Available at: https://www.fraserinstitute.org [Accessed 16 March 2025].

Gartner, 2021. *Predictive Maintenance and Asset Performance Management in Mining,* Stamford: Gartner Research.

Hancock, P. & Moffat, K., 2018. Cybersecurity in Mining : Protecting Digital Infratructure. *Journal of Mining Science and Technology.*

Kalaba, M. & Simatele, M., 2021. Challenges of technology adoption in resource-based economies: Case of sub-Saharan mining. *Extractive Industries and Society,* 8(4), p. 100982.

KPMG, 2022. *Risks and Opportunities for Mining 2022.* [Online] Available at: https://home.kpmg [Accessed 10 April 2025].

Kumar, R. & Deb, S., 2019. Smart mining technologies: Enhancing productivity and sustainability in mining. *International Journal of Mining Science and Technology,* 29(5), pp. 665-672.

Kumar, S., Kumar, P. & Shankar, R., 2020. Real-Time Data Analytics in Mining: A Review. *Interational Journal of Mining Science and Technology.*

Lasi, H., Fettke, P., Kemper, H. & Hoffman , M., 2014. Industry 4.0. *Business and Information Systems Engineering,* 4(6), pp. 239-245.

Lööw, J., Nygren, M. & Johansson, J., 2019. Automation in Mining: Challenges and Opportunities. *Minerals Engineering.*

Makopa , T. & Musiyarira, H., 2022. Challenges and opportunities of mining digitalization in Zimbabwe. *Zimbabwe Journal of Science & Technology,* 17(1), pp. 45-57.

Mawowa, S., 2023. *Technology adoption in Zimbabwe's platinum mining sector: An emerging trend,* Harare: University of Zimbabwe Press.

McKinsey & Company, 2017. *Digitalization in Mining: Unlocking Productivity and Efficiency.* s.l.:McKinsey & Company.

McKinsey & Company, 2020. *How digital innovation can improve mining productivity.* [Online] Available at: https://www.mckinsey.com [Accessed 30 January 2025].

Mensah, B. & Twumasi, D., 2020. Evaluation of mining technology impact on production efficiency. *Journal of Sustainable Mining,* 19(1), pp. 27-34.

Metals, I. C. o. M. a., 2021. *Innovation for a safer and more productive mine.* [Online] Available at: https://www.icmm.com [Accessed 18 January 2025].

Ministry of Mines and Mining Development , 2020. *Strategic Roadmap to the Achievement of a US$12 Billion Mining Industry by 2023,* Harare: Government of Zimbabwe.

Navarra, A., Paraszczak, J. & Fytas, K., 2017. Real Time Monioring in Mining: A Review. *International Journal of Mining, Reclamation and Environment.*

Nguyen, P. & Patterson, L., 2020. AI-Driven Adaptive Mining Operations. *Mining Technology Review,* 3(7), pp. 89-102.

Nhleko, S. & Mabaso, D., 2023. Pilot testing of automated systems in underground mines. *South African Journal of Mining Engineering,* 12(2), pp. 101-115.

OECD, 2020. *Digital Transformation in Extractive Sector,* Paris: OECD.

Paraszczak, J. & Fytas, K., 2012. *Automation in Mining: A Review of Recent Developments.* s.l.:Mining Technology.

Parreira, F., Silva, J. & Santos, L., 2021. Automation in underground mining: Case studies and future outlook. *Mining Engineering Journal,,* 73(4), pp. 24-32.

Rio Tinto, 2019. *AutoHaul™: The world's first automated heavy-haul rail network.* [Online] Available at: https://www.riotinto.com [Accessed 28 April 2025].

RioTinto, 2016. *Autonomous Haulage Systems: A Cae Study.* s.l.:Rio Tinto Group.

Smith R, 2021. Impact of Predictive Maintenance in Autonomous Mining Fleets. *Mining Innovations Review,* 4(9), pp. 201-215.

Smith, R;, 2023. AI- Drien Maintenance for autonomous mining equipment. *Mining Innovations Review,* 2(12), pp. 178 - 192.

Takahashi, H. & Williams, B., 2023. Swarm Intelligence in Autonomous Mining. *AI in Engineering Journal,* 4(9), pp. 144-162.

UNCTAD, 2021. *Harnessing Tecnological Chnage for Inclusive and Sustainable Development in the Mining Sector,* Geneva: United Nations.

Van der Heijden, T., Kiggundu, R. & Lutaaya, P., 2021. Assessing digital readiness in African mining operations. *Development Southern Africa,* 38(5), p. 765–780.

World Bank, 221. *Mineral Reources for Development: Policy and Pratice in the Digital Era,* Washington D.C.: World Bank.

World Economic Forum, 2020. *The Future of Mining: Towards a Digital and Sustainable Mining Industry,* Geneva: WEF.

Zhang, L. J. & Song, W., 2020. Real-time monitoring and predictive maintenance in mining operations. *Journal of Mining Science and Technology,* 30(2), pp. 198-206.

Zhang, Y., Liu, Y. & Wang, J., 2019. Telematics and GPS Technology in Mining: A Review. *Journal of Mining Science and Technology.*