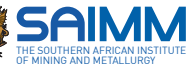
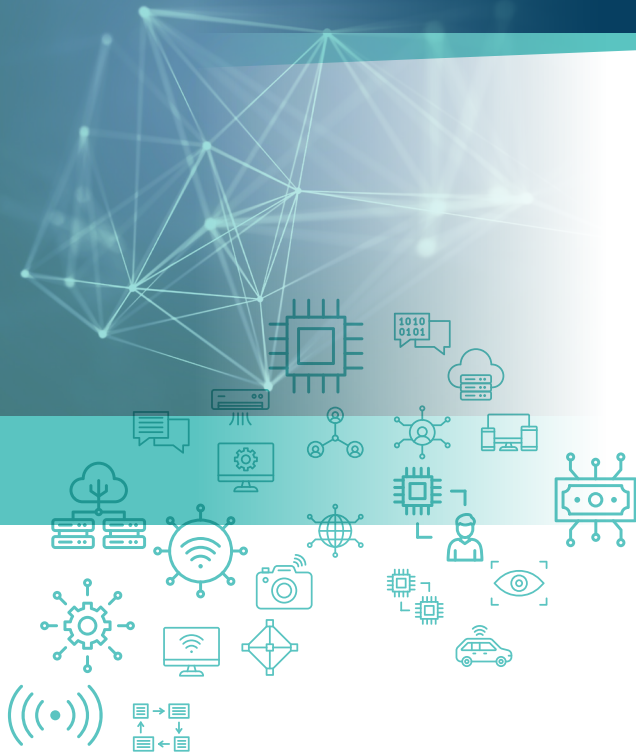




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FOREWORD

SAIMM Digital Transformation in Mining Conference

It is my great privilege to welcome you to the SAIMM Digital Transformation in Mining Conference — a timely and vital gathering focused on shaping the future of our industry through technology, collaboration, and innovation.

Mining is undergoing a fundamental shift. Facing increasing pressures around efficiency, safety, environmental stewardship, and social responsibility, we can no longer rely on conventional methods alone. Digital transformation offers us the tools to reimagine how we explore, extract, process, and deliver mineral resources in a more agile, intelligent, and sustainable way.

But transformation does not happen in isolation. It requires alignment between operational realities and technological ambition. It calls for cross-disciplinary collaboration, open dialogue, and a shared commitment to solving the right problems.

This conference is designed to do exactly that. Across case studies, expert panels, and solution-driven discussions, we will explore what's working, where the challenges lie, and how we can collectively accelerate progress — responsibly and pragmatically.

As chairperson, I encourage you to engage fully, challenge boldly, and connect widely. The future of mining is being shaped today. Let us ensure it is one we can all be proud of.

With the next mining boom imminent, it is crucial that we are ready to take full advantage with the tools in place for the benefit of our companies and South Africa.

Welcome, and thank you for being part of this important journey.

Wouter Broodryk

Conference Chairperson

Corporate Process Specialist – Implats

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Assessment of modern training innovations for supervisors and trainers in the South African mining sector

M. van Schoor¹, N. de Kock², S. Khan¹, R. Müller³, R. van Rensburg³, K. Govindasamy⁴, W. Botha⁵,
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As the mining industry modernises, skills development needs to be a priority. The aim of this paper was to develop guidelines that consider the assessment of modern training solutions for supervisors and trainers in modern mining. A literature review was conducted on best-practice criteria for the evaluation of modern mining upskilling and reskilling solutions. A draft evaluation matrix was developed based on the literature review insights and incorporated 48 best-practice criteria for the assessment of training solutions. The assessment instrument was applied to training curriculums for supervisors and trainers of two participant entities. Data gathering included assessments of the training solutions, and an industry panel review process. Strengths, weaknesses, opportunities, threats, and gap analyses were undertaken. Key insights were revealed for the respective training solutions. Recommendations included continuous review and improvement of the curriculum for alignment to mining modernisation skills needs, including consideration of modern training methodologies and facilitation; revised content and assessments; skills and training required for modernisation; tracking of graduates and learner feedback; better alignment with modernisation objectives and industry skills needs, increased focus on safety and risk assessment and control; and more immersive learning experiences. While sample training innovations were selected for evaluation, the recommendations remain relevant for training entities looking to align to their curriculum to mining modernisation skills needs and industry skills demands for modernisation.

Keywords: Training Curriculum, Training Evaluation, Modernisation, Reskilling, Upskilling

INTRODUCTION

The Successful Application of Technologies Centred Around People (SATCAP) programme of the Mandela Mining Precinct focuses on understanding the impacts of mining modernisation on people in the minerals sector, and intends to support the mining industry's environmental, social and governance agenda. To this end, relevant projects have been commissioned with an emphasis on jobs, skills and people-centric modernisation. This paper provides a summary of the findings from the SATCAP Work Package (WP) 2.1 project in the 2024 financial year. The aim of the project was to develop a guideline for the South African mining industry through assessments of upskilling and reskilling training innovations to drive modern mining skills development for supervisors and trainers.

This project is linked to SATCAP WP 2.2 which also focuses on skills development innovations, but has an outward focus on community members, therefore there are differences in the criteria used and the assessed solutions. However, because of the linkage, there is substantial overlap between this paper and the SATCAP WP 2.1 paper, titled ‘Assessment of waste management and renewables-related training innovations towards mining sustainability.’

Skills development needs to be a priority as the mining industry continues to change and modernise. The modernisation of mines introduces new ways for mine supervisors and trainers to conduct activities. Although the role of supervisors is viewed as critical, there is a missing link between strategy and the implementation of innovative solutions; the sustainability of the sector is dependent on requisite skills development. Relevant skills development will provide employees with the skills required for modern mining and post-mining, thereby enabling modernisation. Furthermore, many of the same skills, especially much-needed digital skills and their application, are relevant for other sectors, including construction, manufacturing and agriculture, and may allow for job options post-mine closure.

REVIEW OF LITERATURE

A literature review was conducted to obtain a deeper understanding of the modern mining skills needed for supervisors and trainers, and to identify best-practice criteria that can be used to assess existing modern mining skills development training solutions. Figure 1 illustrates the core focus areas.

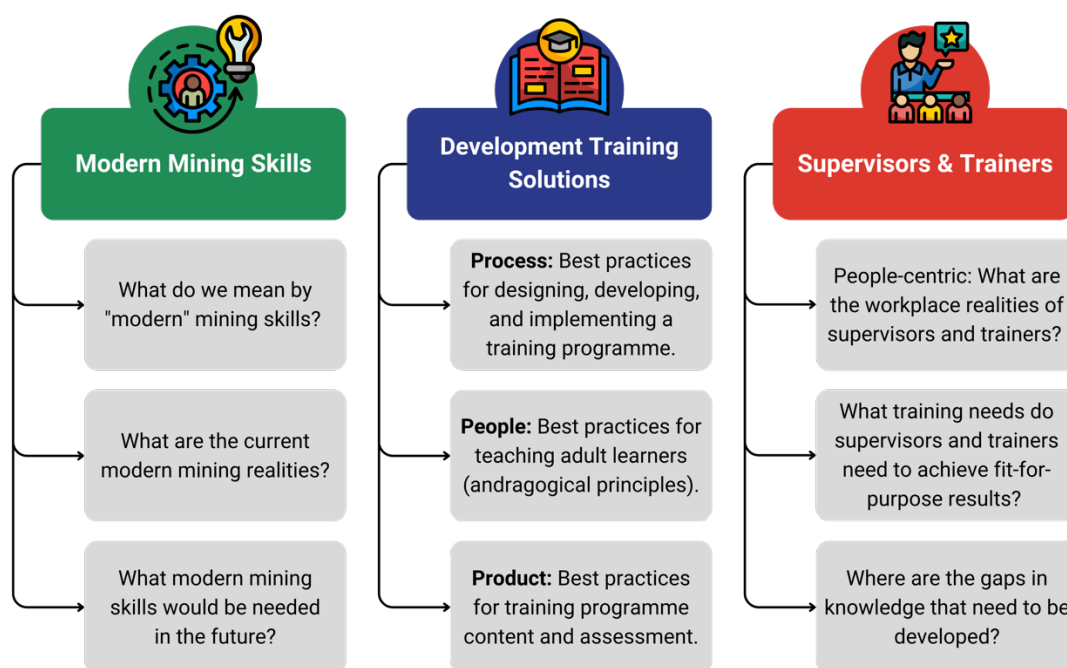


Figure 1 Literature review core focus areas.

Modern mining skills development for supervisors and trainers

Modernisation in mining – defined as the shift from traditional methods to advanced technologies and practices – requires evolving skills for all workers, including supervisors and trainers, to effectively adapt and lead in increasingly complex operations (Global Mining Guidelines Group, 2019). The adoption of technology to conduct mining activities (for example, through mechanisation) has, in some cases, replaced manual tasks. Furthermore, the implementation of automation, which constitutes digital

and autonomous mining technologies, reshapes the roles and skills of the workforce (Fraser, 2017; Jacobs and Webber Youngman, 2017). The training content for supervisors and trainers must be adapted to ensure successful implementation of various technologies. Mine supervisors and trainers should generally understand that legal, operational, health and safety, environmental, communication, and logistical changes are introduced by these technologies (Hattingh *et al.*, 2010; Global Mining Guidelines Group, 2019; Lynas and Horberry, 2011; Willis *et al.*, 2004). It is therefore critical that mine supervisors and trainers are given the relevant training for the diverse array of competencies necessary for the effective operation and management of advanced mining technologies and processes. The skills include digital literacy and technology proficiency; immersive learning and virtual reality (VR) training; advanced technical skills; health and safety management; gamified and mobile micro-learning; educational technology solutions; cross-industry collaboration and innovation; and adaptability and lifelong learning (Minerals Council South Africa, 2024).

Effective training for mining supervisors and trainers must address behavioural skills, digital literacy, and safety culture to support technological advancements (Haywood, 2022; Mape, 2020). Some of the key focus areas include encouraging safety awareness; enhancing digital literacy and acumen for effective training and supervision on, and use of new equipment; proficiency in innovative training methods like gamification and VR, and knowledge of the Mine Health and Safety Act (MHSA) (Moodley, 2018). Supervisors must adapt to automation, the internet of things, and artificial intelligence mentor teams, and leverage modern technologies to enhance productivity and efficiency (Gleeson, 2023; Rawden, 2024). Existing skills training in South Africa appears to emphasise management, leadership, and technical mining competencies, with less focus on modernisation technologies and their operational effects (MQA, 2024).

Reskilling and upskilling are critical for modernising the mining workforce, allowing mines to adapt current employees rather than relying on external hires (Makonese, 2024). Upskilling enhances existing skills, while reskilling equips workers for new roles in modernised environments (Cloud Assess, 2024). Reskilling includes foundational training in new technologies, transitioning roles, and readiness evaluation (Cloud Assess, 2024). A collaborative blueprint involving education institutions, mining companies, and technology providers ensures a future-ready workforce (Ling, 2022; Makonese, 2024). Effective reskilling programs identify trends, skills gaps, and delivery methods, engage stakeholders, and incorporate feedback to improve success (Cloud Assess, 2024). Modern training methods found to be effective include blended learning (70-20-10 model); Learner Management Systems for content delivery and tracking; interactive and gamified methodologies, immersive VR, and simulators; internal training or seminars; and bridging programs to develop science, technology, engineering and mathematics skills for adults (Haywood, 2022; Mape, 2020; Moodley, 2018). Retraining also plays a key role in adapting employees to new job responsibilities due to technological advancements (Cloud Assess, 2024).

In summary, findings from the literature review indicated that any curriculum changes or enhancements to enable modernisation should consider the following, amongst other factors:

- Legal requirements/compliance changes
- New or updated manuals, operating procedures
- New safety, health and environmental hazards and mitigation measures
- Reviews of performance measures and on-job assessments
- Leadership development and coaching
- Effective ways of communication and engagement
- Changes in equipment/machinery/hardware maintenance processes
- Changes in logistics (transport of materials needed for daily shift activities)
- Changes and advancements in technologies
- Training and skills development (digital, technical, safety and health, technology proficiency)
- Modern training methodologies; and
- Change management.

Best-practice criteria

In the literature review, important frameworks with which to create best-practice criteria to evaluate training were also identified.

The foundational framework used was the ISO Standard for Competence Management and People Development (cf. International Organization for Standardization, 2019:v). The ISO standard, with the Plan-Do-Check-Act (PDCA) cycle, serves as a recognised guideline for good quality management. The PDCA cycle includes the process to plan for competence development, aligns the requirements from a business or institutional perspective, and provides guidance for implementation and continuous improvement.

The ISO PDCA Cycle was enhanced using an instructional design framework called the Analysis, Design, Development, Implementation, and Evaluation (ADDIE) model (Florida State University, 2024), to provide extra depth to what is needed when developing a training programme. A Training Needs Analysis forms part of the first step of the PDCA cycle and ADDIE and refers to a systematic process to assess individuals' current knowledge, skills and application against the competence criteria as set by the business or institution.

The third framework used to enhance the PDCA cycle was the Kirkpatrick and Phillips model. This framework aligns with the Check step, as it provides a guideline by which to assess the learner experience and learning within the competence approach. This model is an internationally recognised tool for evaluating and analysing the results of educational, training and learning programmes with a learner-centric approach. It consists of five levels of evaluation: Reaction, Learning, Behaviour, Results, and Return on Investment (ROI) for an amplified business or institutional perspective (Ashofteh and Orangian, 2021; Kirkpatrick and Kirkpatrick, 2013; Phillips, 1998).

The importance of following a systems approach was also identified when developing the best-practice evaluation matrix. Factors to consider when setting evaluation criteria include the learning environment, learner readiness, teacher orientation, learning contents, and if learning is fit for purpose (contextual relevance). The demand for specific competence requirements from a business and social perspective should always inform how evaluation criteria are set – in this case, the modern mining skills necessary for supervisors and trainers. If these demands and requirements are not considered, the learning programme will be less effective.

METHODS

The project followed a design and assessment process that considered the evaluation of modern training solutions for trainers and supervisors. A mixed methods approach was taken to achieve the project objectives. Figure 2 shows the project process flow and activities.

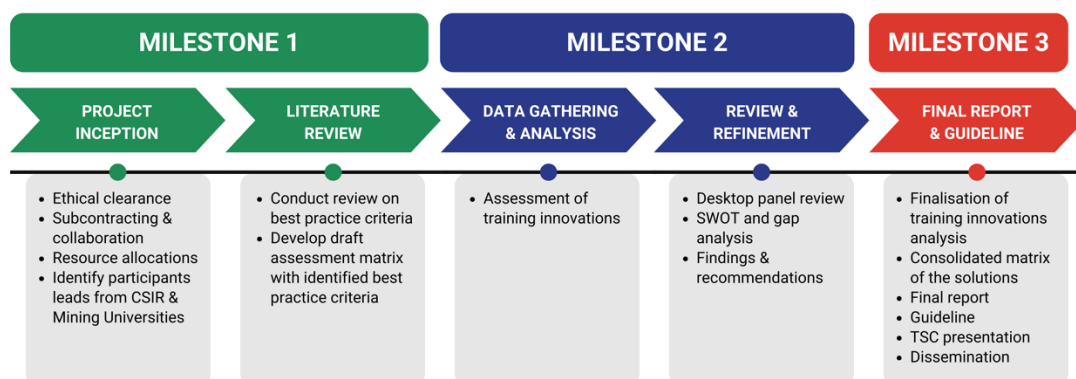


Figure 2. Process flow of project activities.

A literature review was conducted on upskilling and reskilling best-practice criteria for the development of modern mining skills, to support the development of a training innovations assessment tool. A draft evaluation matrix which incorporated best-practice criteria for the assessment of training solutions was developed. The criteria were aligned with the PDCA model, and the ADDIE instructional design framework, and were categorised into the three sub-areas of people, process, and product. Input relating to the design and application of the best-practice criteria as an assessment tool was also obtained from an industry review panel, providing credibility to the evaluation matrix and subsequent evaluation process. The review panel members were selected based on their expertise in the mining industry and skills-related subjects and included individuals from the SATCAP Technical Steering Committee, Minerals Council South Africa (MCSA), Mining Qualifications Authority (MQA), and mining companies. The initial evaluation matrix developed had 76 best-practice criteria, but this was later refined to a streamlined 48-criteria version.

Engagements were held with training provider entities, and the assessment instrument was applied to selected training solutions for trainers and supervisors. Two training providers were identified for participation and included a state-owned entity and a mining university. Purposive sampling was used to select the participating training providers, based on their knowledge and expertise in providing training to supervisors and/or trainers. The data gathering was undertaken in an interview format, either virtually or in-person. The best-practice criteria matrix was used to guide interviews with the training providers related to the selected training offerings. Further data gathering included an industry panel review process to obtain expert input into the analysis of the assessed training curricula. The application of the evaluation matrix provided insight into the respective strengths, weaknesses, opportunities and threats (SWOT) of the training solutions for supervisors and trainers, and recommendations towards closing the gaps or taking advantage of opportunities. The findings would enable training providers to adjust their curricula to meet industry skills demands for sustainable modern mining. Ethics exemption was received for the project from the CSIR Research Ethics Committee.

RESULTS AND DISCUSSION

Assessment tool

Based on insights from the literature review, an assessment tool in the form of an evaluation matrix was developed to evaluate the training programmes for supervisors and trainers. The best-practice criteria included a planning and delivery approach, work integrated learning, instructional design principles, and the integration of learning (process, people, and product). The evaluation of the training solutions in terms of PDCA methodology considers:

- **Plan:** Industry needs and skills gaps, and curriculum design
- **Do:** Curriculum relevance, and curriculum delivery
- **Check:** Evaluation/review; and
- **Act:** Continuous improvement, and future foresight.

The evaluation matrix has key focus areas with associated criteria for assessments, assessment questions, and assessment ratings. The revised matrix further includes a consolidated and heatmap summary view, that includes interviewee comments. The following is noted:

- The PDCA cycle serves as the base for the criteria
- Supporting models and approaches are included in each step of the PDCA cycle, to enhance the validity of the criteria and ensure that it is comprehensive and covers all necessary fields in terms of the process, people, and product of training interventions; and
- The evaluation matrix is informed by the skills needed and the best approach to develop the requisite modern knowledge, skills and application for the mining industry.

A snapshot of the best-practice criteria evaluation matrix is shown in Table 1, while a summary of the refined best-practice criteria is shown in Figure 3. This project guideline containing the evaluation matrix is available on the Mandela Mining Precinct website, for use by industry training entities. When applying the tool, it is important to consider that it should not be used as a tool for measuring the value of a training offering, given the context of mining modernisation; but rather used to highlight opportunities for improvements.

Table 1. Snapshot of the training assessment best-practice criteria evaluation matrix

ISO PDCA Phase:		PLAN				
ADDIE Step(s):		ANALYSIS				
Best-Practice Criteria		Evaluation Questions:	Assessment:			Recommended action to close the identified gap or change a weakness into a strength or take advantage of an opportunity to improve:
Identify industry needs & skills gaps			NO (Strong Weakness)	Partially (Weakness)	YES (Strength)	
PROCESS	Evidence-based Training Needs Analysis	Has an evidence-based Training Needs Analysis been conducted to identify the training requirements for mine supervisors and trainers?	No TNA done.	Yes, a TNA was done but subjective or not focussing on supervisors & trainers.	Yes, an evidence-based TNA was done for supervisors & trainers.	
	Multiple source data collection	Has comprehensive data been collected from multiple sources (e.g., surveys, interviews, performance reviews) to identify training needs?	No data was collected.	Yes, data was collected but not from multiple sources.	Yes, data was sourced from multiple sources.	

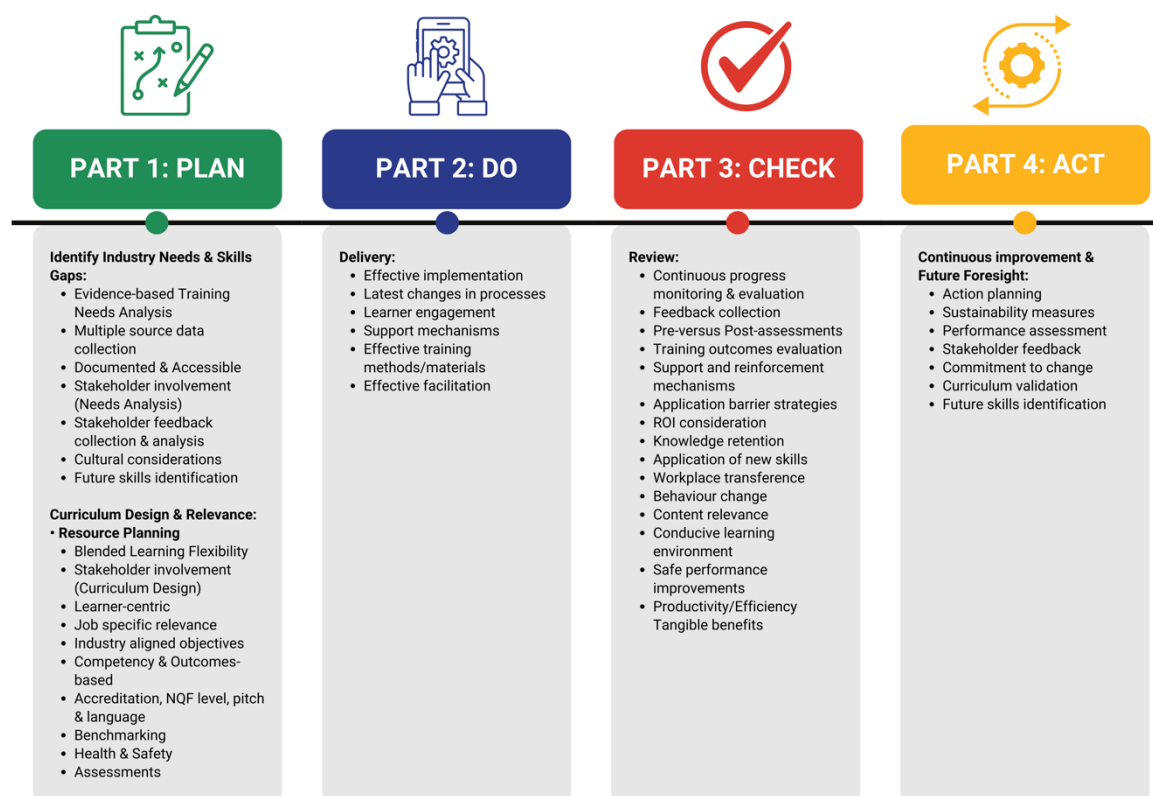


Figure 3. Summary of the refined best-practice criteria used for the training assessment.

Assessment results

Two training providers participated in this project (anonymised). Assessments were conducted for two training solutions offered by each provider. A summary of the training courses that were assessed is shown in Table 2.

Data collection was conducted by applying the developed best-practice evaluation matrix, and these findings were used to conduct a SWOT analysis for each of the assessed training innovations. Key insights were revealed for the respective training innovations towards meeting the industry skills demands and training needs for trainers and supervisors. The process of assessment and the analysis of data enabled areas of strengths and areas for potential improvement to be highlighted. Review by the industry panel also contributed to findings and recommendations. The primary objective of the panel review was to gain an understanding from an industry perspective and whether the training solutions that were considered were meeting and addressing the skills and training demands for a modernising landscape.

Table 2. Training assessments conducted

Trainer A	Trainer B
Training innovation A1 is an NQF level 8 Bachelor of Engineering (BEng) semester course aimed at undergraduates. The module is presented in English in a classroom-based setting and comprises three lectures and two tutorials per week.	Training innovation B1 is a Safety Awareness Training short course aimed at new and returning industry employees. The module is presented in English in a classroom-based setting and comprises eight hours (1 day) of instruction.
Training innovation A2 is a short course that is open to mining industry representatives and provides the learner with a theoretical background on the topic of Geotechnical Engineering. The course is presented over five days and allows interaction between the facilitator and the students.	Training innovation B2 is also a 1-day / 8-hour Emergency Response short course that is open to mining industry representatives – preferably candidates with basic literacy and numeracy knowledge and a minimum of two years underground experience (advised).

A direct comparison of individual offerings was not advised but was considered insightful to identify common and recurring themes across all the assessments that were done, to highlight and even grade the major pain points (weaknesses and threats) and also the stand-out positive aspects (strengths and opportunities) that emerge. To this end, a semi-quantitative and partly subjective scoring system was applied to a consolidated matrix of the assessment results. For each positive response ('Yes'), a score of +2 was assigned. 'Partial weakness' responses were assigned a score of -1, while strong negative responses ('No') were assigned a score of -2. The scores were tallied to yield a cumulative score for the complete list of the 48 best-practice criteria. The grading approach that was applied based on the cumulative scores is shown in Table 3. The consolidated matrix (heatmap) of results is shown in Figure 4. As the results may primarily be of significance to the participant entities to remediate or enhance their curriculum, they are not discussed in detail in this paper. However, the results have relevance to training entities in need of aligning their curricula towards modernisation skills development efforts.

Table 3. Grading approach

MIN	MAX	RATING COLOUR	
-8	-3		A cumulative score of between -8 and -3 indicates the most concerning weaknesses
-2	0		A cumulative score of between -2 and 0 indicates less concerning, but arguably still important weaknesses
1	3		Cummulative scores of between 1 and 3 can be considered as neutral
4	8		Cummulative scores of between 4 and 8 can be viewed as prominent strengths

		Best-Practice Criteria			Assessment (A1):			Assessment (A2):			Assessment (B1):			Assessment (B2):			Score	Rating colour
		NO (Strong Weakness)	Partially (Weakness)	YES (Strength)	NO (Strong Weakness)	Partially (Weakness)	YES (Strength)	NO (Strong Weakness)	Partially (Weakness)	YES (Strength)	NO (Strong Weakness)	Partially (Weakness)	YES (Strength)					
PART I - PLAN	Identify industry needs & skills gaps																	
	PROCESS	Evidence-based Training Needs Analysis		2		-1							2	3				
		Multiple Source Data Collection		2		-1							2	3				
		Documented & Accessible		2		-1					-2			-1				
	PEOPLE	Stakeholder Involvement (Needs Analysis)		2		-1							2	3				
		Stakeholder Feedback Collection & Analysis		2			2	-2					2	4				
		Cultural Considerations		2			2			2			2	8				
	PRODUCT / OUTPUT	Future Skills Identification		2			2	-2					2	4				
		Curriculum Design & Relevance																
	PROCESS	Resource Planning		2			2			2			2	8				
		Blended Learning			2	-2				-1				2	1			
		Flexibility	-2				-1				2			2	1			
	PEOPLE	Stakeholder Involvement (Curriculum Design)			2			2			2		-1	5				
		Learner-Centric		-1			-1		-2				2	-2				
		Job Specific Relevance			2			2		-1				2	5			
	PRODUCT / OUTPUT	Industry Aligned Objectives			2			2	-2				-1	1				
		Competency & Outcomes-based			2		-1			-1				2	2			
		Level & Language			2		-1				2			2	5			
		Benchmarking			2			2			2			2	8			
		Health & Safety		-1			-1								-2			
		Assessments		-1			-1							2	0			
PART II - DO	Best-Practice Criteria																	
	Delivery																	
	PROCESS	Effective Implementation		2			2	-2				-1		1				
		Latest Changes in Processes			2			2		-1				3				
	PEOPLE	Learner Engagement			2		-1			-1			2	2				
		Support Mechanisms			2			2			2			8				
	PRODUCT / OUTPUT	Effective Training Methods/Materials			2		-1			-1			2	2				
		Effective Facilitation			2		-1				2			5				
	PART III - CHECK	Best-Practice Criteria																
		Review																
PROCESS		Continuous Progress Monitoring & Evaluation			2		-1				2			3				
		Feedback Collection			2			2			-1		-1	2				
		Pre- versus Post-Assessments		-1		-2				-1			-1	-5				
		Training Outcomes Evaluation			2			2						6				
		Support and Reinforcement Mechanisms		-1				2	-2			-2		-3				
		Application Barrier Strategies		-1			-1				2		-1	-1				
		ROI Consideration	-2			-2		-2				-2		-8				
PEOPLE		Knowledge Retention			2		-1			-1				2	2			
		Application of New Skills			2			2			2			2	8			
		Behaviour Change			2			2			2		-1		5			
		Workplace Transference	-2					2			2			2	4			
PRODUCT / OUTPUT		Content Relevance	-2					2			2			2	4			
		Conducive Learning Environment			2		-1			-1			-1		-1			
		Safe Performance Improvements			2			2			2			2	8			
		Productivity/Efficiency			2			2			2				6			
		Tangible Benefits			2			2			2				6			
PART IV - ACT	Best-Practice Criteria																	
	Continuous Improvement & Future Foresight																	
	PROCESS	Action Planning			2	-2					2	-2		0				
		Sustainability Measures			2			2	-2					2				
	PEOPLE	Performance Assessment			2			2			2			2				
		Stakeholder Feedback			2		-1			-1				2	8			
		Commitment to Change			2			2			2			2	8			
	PRODUCT / OUTPUT	Curriculum Validation			2			2			2			2	8			
Future Skills Identification				2		-1				2			2	5				

Figure 4. Consolidated matrix of assessment results.

CONCLUSION AND RECOMMENDATIONS

This project benefits both the mining industry and training providers. The value for the industry lies in the guidance that will enable them to identify training offerings that are aligned with best-practice training criteria, given the context of mining modernisation. Meanwhile, training providers can use the learnings from the project to design new and enhance existing offerings to remain at the cutting edge of providing training solutions for industry. Conclusions based on the assessment results are shown in Table 4.

Table 4. Summary of assessment results

Most concerning weaknesses	Other perceived weaknesses
• Pre- vs Post-Assessments: generally, learners' skills were not assessed before and after the training to determine new skills/upskilling and reskilling needs; it is mostly done only at the end of the training. • Support and Reinforcement Mechanisms: it appears that there were often no mechanisms in place to support effective application on the job. • ROI Consideration: the concept of ROI does not generally feature for the training programmes that were assessed.	• Documented and Accessible: competence gap analysis results were not usually documented. • Learner-centric: training programmes are generally not tailored to meet the specific modernisation skills needs. • Health and Safety: the training offerings do not necessarily equip supervisors and trainers with hazard, risk assessment and control measure information of the modernisation technology. • Application Barrier Strategies: remedial/reinforcement strategies are not offered post upskilling/reskilling/new skills development. • Conducive Learning Environment: the training environment is not always considered to be conducive to learning (e.g., comfortable, well-equipped, with modern machines/technologies for learning). • Action Planning: it emerged that specific actions were not always planned or implemented to address gaps or areas for improvement.
Most prominent strengths	Most prominent strengths

• Cultural Considerations: cultural factors and diversity aspects were generally considered; sometimes part of accreditation visits, advisory board meetings or part of professional body's requirements and demands. • Resource Planning: the necessary internal, competent resources (e.g., budget, materials, faculty) were allocated for the training programmes. • Benchmarking: curricula were mostly aligned with OEMs' standards and operating manuals, best-practices as well as future skills requirements. • Support Mechanisms: support mechanisms were put in place to guide learners to relearn new behaviours and unlearn old behaviours during the training. • Training Outcomes Evaluation: training outcomes were evaluated against the predefined modernisation/technology use and upskilling/reskilling objectives. • Application of New Skills: learners were enabled to apply the skills gained from the training in their job or in the training of workers/communities.	• Productivity/Efficiency: the training contributed to increased efficiency due to improved skills to deliver training/ supervise in the modern mining landscape. • Tangible Benefits: the training offerings considered seem to yield benefits, such as improved safe production, a better skilled workforce, upskilled supervisors and trainers as a result of the training. • Stakeholder Involvement: key stakeholders (e.g., industry experts, trainers, supervisors) were mostly involved in setting the learning criteria for the training programme and its assessments; learning criteria were also sometimes aligned with company values. • Job-specific Relevance: the curricula were generally considered relevant to the job roles and responsibilities of supervisors and trainers to support and enable modernisation; for example, where fundamentals of mine safety is taught. • Level and Language: training was pitched at an appropriate level considering the educational level of participants and their language. • Effective Facilitation: the trainers generally had the necessary capacity, capability, qualifications and competence to deliver the modernisation content and address learner new skills needs; however, it should be noted that in some cases, technical roll-out and capacity constraints were observed. • Behaviour Change: it was mostly agreed that the reskilling/ upskilling and new skills development allowed for observable behaviour changes of supervisor and trainers; it was commented however that it was difficult to observe change in behaviour in the workplace and that employers should be better positioned to observe this. • Future Skills Identification: the faculty skills and competence requirements were generally assessed, to give faculty the required capacity development to support future skills demands; for example, allowing for additional lecturing staff for delivery.
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Considering the consolidated analysis presented above and recommendations that were made based on individual SWOT analyses, the following consolidated recommendations can be made for training providers that either want to improve an existing training offering (in the broad context of mining modernisation), or for those wanting to develop a new offering:

- Maintain and build on existing or identified strengths, and do continuous review and improvement as the landscape changes for updates around training methodologies, content, facilitation, assessment and learner feedback approach, modernisation skills and training needs
- Better align curriculum with modernisation objectives to meet industry skills demands
- Investigate initiatives to keep track of graduates to perform post-study validations
- Better align the assessment criteria with modernisation skills needs
- Better align the curriculum with modernisation objectives and stakeholder needs; to this end, professional bodies should be lobbied for input
- Include more focus on safety and risk assessment/control measures in line with the use of modern technologies
- Introduce more immersive learning experiences and afford opportunities for practice or

practical exposure

- Continual improvement based on learner feedback
- Take advantage of opportunities created in the industry to stay on top of the latest modernisation strategies to continuously align and improve training interventions
- Investigate how linkages with industry and the Department of Mineral Resources and the Environment, can be leveraged to secure additional funding to support and sustain and even expand current offerings
- A key to continual improvement is through learner feedback
- Investigate post-training opportunities in collaboration with industry - for example, behaviour change feedback, on the job application and remedial/reinforcement strategies
- Investigate how the concept of ROI can be better quantified, introduced to learners, and related to training offerings; and
- Ensure that continuous improvement and future foresight measures are put in place – for example, through faculty skills and competence assessment and development.

A key consideration is that while sample training innovations were selected for evaluation, the findings and recommendations are relevant to training entities looking to align to their curriculum to mining modernisation skills demands and training needs.

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Competency-based training for mine emergency response

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Mine workers are exposed to hazards that can cause injuries or fatalities, including fires, underground explosions, irrespirable atmospheres, falls of ground, and mobile machinery. Emergency preparedness is important for improved safety outcomes and includes the deployment of self-contained self-rescuer (SCSR) devices, effective escape routes, and adequately located refuge bays. The need has been identified for improved training solutions for mine worker escape situations, which should provide some exposure to the stressors that would be experienced. The CSIR Mining Cluster has developed innovative multi-modal competency-based training modules to improve the emergency response of mine employees. The modules include interactive e-learning, virtual reality training, SCSR donning and breathing simulation, and competency-based assessments. A pilot study was successfully completed with participation from a major coal mining operation. The competency-based approach improves the overall efficacy of the training and is especially well-suited to training for high-consequence, low-frequency scenarios.

Keywords: competency-based training, emergency preparedness, expectation trainer, experiential learning, immersive training

INTRODUCTION

The need for improved training solutions has been identified to improve health and safety awareness and performance, and to reduce the occurrence of injuries and fatalities in the South African mining industry (SAMI). Training capability for emergency scenarios in the industry could be improved through the application of technology. Improved training approaches that have been identified include experiential training, which may involve the use of computer simulation and virtual reality (VR) technology, to improve the level of engagement, quality and effectiveness of safety training. Immersive training can recreate – in a safe and controlled environment – the physical, cognitive, and psychological stressors and behavioural responses that are experienced in emergency situations. These stressors are likely to have an adverse effect on recall and execution of emergency response procedures. By including immersive simulation of emergency scenarios in the training, the retention and performance outcomes in real emergencies can be improved.

The CSIR Mining Cluster has developed innovative multi-modal competency-based training modules to improve the emergency response of mine employees in scenarios that include risk of irrespirable atmospheres. The immersive and experience-based training interventions supplement existing safety awareness training provided by the Kloppersbos fires and explosions test facility. This paper provides a description of the potential application of technology to enhance training capability for emergency scenarios in the SAMI and the development of the immersive training modules by the CSIR. These modules include e-learning, VR training involving simulation of an escape route scenario, simulation of SCSR donning and breathing, and competency-based assessments. Although the training methods employed in this project are not novel, the application of the combination thereof to emergency response training in the SAMI is unique.

REVIEW OF LITERATURE

Emergency preparedness

The mining industry is inherently dangerous, with numerous fatalities and injuries resulting from mining accidents (Andersen *et al.*, 2020; Daniels and Salisbury, 2000; Grabowski and Jankowski, 2015; Hui, 2017; Tichon and Burgess-Limerick, 2011; van Wyk, 2015). Mining industry hazards include fire, underground explosions, toxic gases, geotechnical hazards, and working in close proximity to equipment (Tichon and Burgess-Limerick, 2011). Emergency preparedness is important for improved safety outcomes (Ablah *et al.*, 2009; Cohen *et al.*, 2013; Feng *et al.*, 2018 and 2020; Sermet and Demir, 2019).

A self-contained self-rescuer (SCSR) is an emergency breathing apparatus which allows the user to isolate their respiratory system from an irrespirable atmosphere and which provides a safe source of oxygen for a finite duration. The use of SCSR devices has become common in underground mines in South Africa with approximately 287 000 SCSR units deployed in 201 mines in 2023 (Sehlabana, 2023). When an irrespirable atmosphere occurs, for example as a result of a fire, each worker must don (deploy) their body-worn SCSR and proceed to a place of safety such as an underground refuge bay. The deployment of SCSR devices, the location of refuge bays, and effective escape routes form part of emergency evacuation procedures (Biffi and Sehlabana, 2018). In an emergency, SCSRs provide breathable air and protect the wearers against potentially toxic gases and oxygen deficient atmospheres, to enable them to reach a place of safety (such as a refuge bay) where respirable air is available. Biffi and Sehlabana (2018) note that workers must be proficient in the donning of SCSRs and familiar with emergency evacuation procedures to achieve the life-sustaining capacity of the SCSR. Previously reported failures in donning SCSRs in emergencies included mine workers forgetting to don nose-clips or goggles, not being able to activate the oxygen supply, straps getting tangled with cap-lamp cords, delayed donning, or removing the mouthpiece when experiencing breathing resistance (Biffi and Sehlabana, 2018).

The high rate of accidents and fatalities in the SAMI has frequently been attributed to ineffective training methods and material, and the need for new solutions has been identified, such as the use of VR technology (Daniels and Salisbury, 2000; Grabowski and Jankowski, 2015; Squelch, 2001). More specifically, improvements to the nature and level of mine worker training in escape and rescue operations has been highlighted, including “novel training procedures that will provide an indication of the physical, cognitive, psychological stressors and behavioural responses that would be experienced in traumatic escape situations” (Biffi and Sehlabana, 2018). Biffi and Sehlabana (2018) highlight the application of experiential training for the use of refuge bays and underground emergency procedures, and the potential for the SCSR Expectation Trainer. Additionally, a recommendation arising from a project funded by the Mine Health and Safety Council was to “Implement, as a matter of urgency, experiential and expectation training for the donning and use of SCSRs” (Hodgskiss *et al.*, 2017).

Experiential training methods

Experiential training is considered an effective means to improve mine emergency training. Computer simulation and VR can provide immersive training, in which the trainee has a realistic experience of the simulated scenarios, without the associated risks (Tichon and Burgess-Limerick, 2011; van Wyk, 2015; Zhang, 2020). The use of VR has been cited as an effective method of training in a number of industries and activities, including safety and hazard or risk awareness, emergency response, and evacuation (Chen *et al.*, 2008; Daniels and Salisbury, 2000; Feng *et al.*, 2018; Makransky *et al.*, 2019; Squelch, 2001). The use of VR technologies has also been increasing in the SAMI (Solomons, 2015).

Traditional emergency preparedness training approaches include seminars, posters, manuals, videos, and drills (Andersen *et al.*, 2020; Daniels and Salisbury, 2000; Feng *et al.*, 2018 and 2020; Makransky *et al.*, 2019). Traditional methods of training in the SAMI, in particular, include class-room style learning, video-based training programs, instruction in physical mock-ups of underground workplaces, and on-the-job training (Squelch, 2001). However, limitations to conventional approaches include that they are not highly engaging, and limit sensory reflection of real-life emergency scenarios (Feng *et al.*, 2020;

Tichon and Burgess-Limerick, 2011). Additionally, factors that make training under actual working conditions difficult or impossible include the need to interact with equipment that is expensive, unavailable, or inaccessible; the expense of downtime; dangerous conditions; and that it is not always possible to simulate real dangers or conditions (Andersen *et al.*, 2020; Hui, 2017; Sharma *et al.*, 2017; Squelch, 2001). Further challenges include skills degradation over time, difficulties with skills assessment and feedback, and the evaluation of the effectiveness of training (Cohen *et al.*, 2013; Ford and Schmidt, 2000; Tichon and Burgess-Limerick, 2011).

As an example, VR can be used to supplement or replace traditional methods of training (Squelch, 2001). Potential benefits of VR training noted in previous research (e.g. Bednarz *et al.*, 2010; Cohen *et al.*, 2013; Crichton and Flin, 2004; Daniels and Salisbury, 2000; E&MJ, 2019; Grabowski and Jankowski, 2015; Makransky *et al.*, 2019; Sermet and Demir, 2019; Squelch, 2001; Tichon and Burgess-Limerick, 2011; Zhang, 2020), include:

- Provision of realistic experiences for improved quality of training
- Cost-effectiveness
- Safe environment (e.g. to prevent risk of injury or material damage)
- Possibility for a wide range of scenarios, including those that are rarely experienced in real-life
- Flexibility (e.g., to modify and customise)
- Acquisition and transfer of tacit knowledge
- Training sessions can be conducted for multiple participants
- Trainee interaction (e.g., for physically distant individuals and teams)
- Training can be provided at any location
- Monitoring of progress and understanding during training sessions
- Ability to precisely record and reproduce simulated training exercises; and
- Provision of accurate and immediate feedback.

As such, immersive training experiences can increase mine workers' ability to retain and recall information, and to execute the correct emergency response procedures swiftly and accurately. The physical or virtual immersive training environment can simulate a high consequence scenario without exposing the trainees to the actual safety hazards. Additionally, creating a virtual environment can be achieved at a fraction of the cost of constructing and maintaining a traditional physical environment. Changes in the digital environment are also far more cost-effective.

Competency-based training

There are various definitions for competency-based education (CBE) or competency-based learning (CBL). Within the context of this paper, CBE or CBL is referred to as competency-based training.

Gervais (2016) defined CBE as “an outcome-based approach to education that incorporates modes of instructional delivery and assessment efforts designed to evaluate mastery of learning by students through their demonstration of knowledge, attitudes, values, skills, and behaviours required for the degree sought.” Henri *et al.* (2017) broadly defined CBE as “a pedagogical approach that focuses on the mastery of measurable student outcomes.” Oroszi (2020) defined CBE as “an innovative approach in higher education that organises academic content or delivery according to competencies, what a student knows and can do, rather than following a more traditional scheme, such as by course.”

In essence, CBE is a learner-centred approach (Dyke, 2009) that enables learners to practise the learnings to attain specific skills, as opposed to extensive time spent in a classroom in traditional learning approaches (Oroszi, 2020). Some of the key characteristics of CBE include self-paced learning and flexibility, the use of technology for experiential learning, tailored learning styles (based on student age group and student experience), interactive sessions and assessments, and predefined outcomes. These characteristics are also aligned with those of experiential learning. In addition, CBE aims to improve the retention of knowledge and to impart skills to students that meet the needs of industry (Henri *et al.*, 2017; Oroszi, 2020; Gervais, 2016).

The Republic of South Africa (2000) highlighted three pillars of competence in its National Education Policy Act, 1996:

- Foundational (or theoretical) competence – the learner shows an **understanding** of the knowledge and thinking behind what they are doing
- Practical competence – the learner is able to **do** what they have learned in a real-world environment and is able to **make good decisions** on how to do it; and
- Reflexive competence – the learner is able to **connect** their actions and decisions with their understanding, are able to **adapt to changes** and can **explain** why certain choices are made.

These pillars strongly suggest that theory, practise and reflection play a crucial role in CBE (Dyke, 2009) and are collectively referred to as “applied competence” (Republic of South Africa, 2000). Dyke (2009) inferred that CBE is an enabler for more informed decision-making that would guide a learner’s actions. Dyke (2009) included “interaction” as a fourth pillar for CBE in his framework for “reflexive learning.” Interaction is related to engaging with others in a social or learning context.

The literature indicates that CBE is becoming more widely adopted for various competencies in various industries, including engineering and mining competencies. CBE has become an effective mode of learning to impart skills that meet industry’s needs and to accommodate learners from different backgrounds and circumstances through its flexible approach (Henri *et al.*, 2017).

METHODS

The CSIR hosts weekly mine fire and explosion safety awareness training seminars at the Kloppersbos facility. The seminars are considered an important part of worker safety training, especially for coal mine workers. The seminars include a lecture on fire and explosion risk and prevention, small-scale demonstrations, and large-scale fire and explosion demonstrations. The CSIR has been offering the safety awareness training for many years and approximately 4500 mine workers attend annually. Despite the safety awareness training and the mines’ internal operational and engineering controls, underground fires and ignitions of flammable gas still occur. Mines Rescue Services (MRS) reported a total of 17 fire incidents occurring in South African mines in 2024, of which six were classified as major fires (Mines Rescue Services, 2025).

CSIR invited key industry stakeholders to participate in a workshop to explore how the training in underground mine fire and explosion safety could be enhanced. The broad aim of the workshop was to explore opportunities to increase the effectiveness of mine safety training interventions through experiential training and use of appropriate technology. One of the significant outcomes of the workshop was recognition of the need for better training of mine workers in mine emergency response. Once an incident, such as a fire or explosion occurs, which results in an irrespirable atmosphere, each worker must be able to self-rescue by rapidly donning their SCSR and following the designated escape route to reach a place of safety from where they can be taken to surface by MRS rescue teams. The stakeholder workshop indicated that the quality of existing training of workers in self-rescue procedures varied greatly across the mining industry. Following this outcome, the CSIR partnered with an industry-leading company specialising in the development of technology-enabled training solutions to develop the Competency-based Training in Mine Emergency Response. This novel training framework incorporates e-learning and VR modules as well as experiential training to ensure high learner engagement during the training, resulting in good recall with rapid execution of the emergency response procedure while under the psychological and physical stress of an emergency situation.

The CSIR then did a roadshow with the new training offering to demonstrate it to selected clients and solicit their feedback and recommendations for future developments and improvements.

A pilot study was conducted with a coal mine in November 2023, to test the equipment, process, and programme, and obtain feedback from the learners. The programme was attended by a ventilation and occupational hygiene engineering specialist, training specialist, technician, and learner.

Ethics approval to conduct this project was granted by the CSIR Research Ethics Committee (Ref: 340/2020).

OUTPUTS

The newly developed modules that are described in this section include:

- Interactive e-learning modules on basic emergency response procedures
- Real-life experiential training in SCSR-donning procedures
- SCSR breathing simulation using the CSIR Expectation Trainer device
- VR training involving simulation of an escape route scenario; and
- Competency-based assessments.

Interactive e-learning modules on emergency response procedures

The training course starts with the transfer of the basic knowledge on which the rest of the training will build. This knowledge transfer is achieved by allowing the trainee to work through five interactive e-learning modules at their own pace. The e-learning modules make use of realistic video animations, text captions and voice-over to convey the learning content. This engages both visual and auditory senses of the learner and ensures that it caters for learners with different learning styles. In addition, each component includes an introduction and assessment section. Three primary interactive e-learning components were developed in the Learning Management System (LMS), namely:

- Catastrophic explosions – explosion prevention (two modules)
- Awareness campaign for everyone – lifeline and refuge bay (two modules); and
- Self-rescue (one module).

Table 1. E-learning modules and content

Topic	Content
Overview of Catastrophic Explosions	• Methane Gas (Firedamp) • Coal Dust • Ventilation Issues • Ignition Sources • Structural Failures • Spontaneous Combustion • Human and Systemic Errors • Environmental Factors
Catastrophic Explosion Prevention Tools	• Monitoring and Detection Systems • Ventilation Systems • Explosion-Proof Equipment • Dust Suppression and Control • Barriers and Containment • Spontaneous Combustion Prevention
Explosion Prevention Strategies	• Effective Ventilation Management • Regular Dust Control • Ignition Source Elimination • Training and Safety Protocols • Emergency Preparedness

	• Legislation and Standards Compliance • Continuous Improvement Programs
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Topics covered in the e-learning modules, relating to catastrophic explosions and the prevention thereof, are listed in Table 1. Examples of content relating to the lifeline procedure and SCSR modules are shown in Figures 1 and 2. Benefits of the e-learning modules are that it is self-paced, and can be completed anywhere, provided there is access to a device with internet connectivity.



Figure 1. Example of content in the lifeline and rescue bay training module.



Figure 2. Example of a step in the SCSR donning procedure module.

An assessment is required following the completion of the e-learning modules. A score of at least 90% is required to pass each assessment. Three attempts are permitted. The e-learning system further includes components for uploading the assessment results from the practical components, namely the

SCSR simulation and VR training. A certificate is provided upon the successful completion of all the required components.

Experiential SCSR training and breathing simulation

SCSR training is important as it has been identified that individuals do not follow correct donning procedures in an emergency and lack the experience and feel of real units. As such, in addition to the e-learning training, the SCSR training includes the use of training units obtained from SCSR original equipment manufacturers and the use of the CSIR Expectation trainer device. Training units, or expired SCSR units used in a safe environment, can be used for individuals to practise donning and to learn what to expect when breathing from an SCSR. The use of the Expectation trainer is detailed further below. It is recommended that regular, practical training takes place every six to 12 months.

The purpose of the SCSR Expectation trainer is to improve the training and preparedness of underground mine workers in the use of SCSRs during emergency escapes. The unit simulates the experience of breathing from an SCSR, including factors such as elevated inhalation temperature, elevated resistance, and fitting of nose clips and goggles. The unit provides a realistic inhalation temperature ranging from 40°C to 60°C and a breathing resistance of approximately 1000 Pascal (10 mbar) for both inhalation and exhalation, simulating conditions similar to those encountered when using a real SCSR in an escape scenario. The Expectation trainer does not require chemicals and can be disinfected and reused. Images of the training unit are shown in Figure 3. Overall, the application of the Expectation Trainer serves to enhance miners' understanding of and proficiency in using SCSRs during underground emergencies, improving their chances of successful escape.



Figure 3. Expectation trainer (left) and components (right).

VR training for an emergency escape scenario

The VR experience covers three areas of an emergency escape scenario, namely:

- Donning of the SCSR unit
- Finding the lifeline and route to the refuge bay; and
- Refuge bay procedures.

Examples of images from the VR training are provided in Figures 4 and 5.

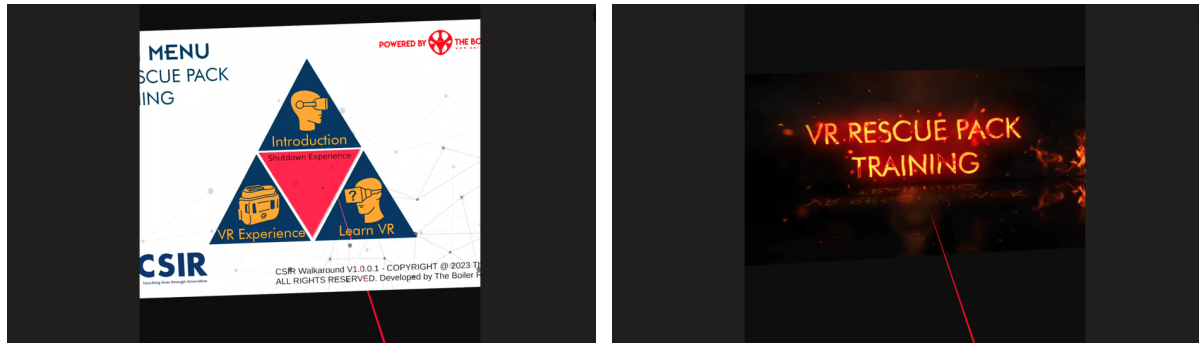


Figure 4. Main menu of VR training module.



Figure 5. Example of VR training for an escape route scenario.

During the training, the facilitator needs to ensure that the following activities have been completed by the learners once having entered the refuge bay in the VR environment:

- Check and test for methane gas
- Activate the positive vent flow at the borehole
- Instruction to remove SCSR units
- Check and apply first aid to any individual in need
- Take register of team numbers
- Inform control room of status and needs of the team
- Check status of toilet facility
- Keep only one headlight on to preserve and save energy of other lamps; and
- Stay calm and wait patiently for rescue team to arrive.

These modules train the workers to rapidly respond to emergency situations. By including an appropriate level of assessment in each module the trainer can confirm if each trainee is competent or needs further training.

Pilot study feedback

Feedback on the training was provided following a pilot study of the modules with participants from a mine, in terms of the e-learning modules, VR modules, and use of the Expectation trainer. Images taken during the pilot study are shown in Figure 6.

Each of the learners completed at least one of the e-learning modules and assessments that followed. All of the learners indicated that the content was exciting, interesting, and easy to follow. They indicated that the way it was presented captured their attention and kept them engaged to the end. The LMS structure and layout was considered easy to navigate and manage.

The VR module provided an underground mining experience. Some of the learners battled to find their way through the course from donning the SCSR to getting to the rescue bay. It was clear that experience at an underground operation and the emergency response procedure played a major role. The learner who did not have mining experience battled more than the other learners to complete the module. All learners had to repeat a section or module more than once to get to the rescue bay. In addition, the following aspects played a major role in the success of the module:

- Previous experience playing computer games
- Familiarisation with VR technology
- Computer and technology orientation; and
- Experience in dealing with nausea.

Despite the above challenges, all the participants reported the training to be exciting and that it was good to use technology to enhance the training experience and they would explore and use the headset.

The Expectation trainer provided the learners with the heat and breathing resistance typically associated with the use of SCSR units. All candidates used and tried the Expectation trainer with great anticipation. The trainees indicated that the experience was different to only using a training unit and felt much more uncomfortable, warm, and more like the real-life units. The nose clip provided some challenges for individuals with a small nose construction as it kept slipping off.

The pilot program was considered a valuable experience and opportunity to test the equipment. It also captured feedback from the learners in terms of the content and process. The program is expected to add value and increase competency in emergency response training. Moreover, the following aspects need to be considered when nominating individuals for this course:

- **Literacy level:** It is recommended that individuals need at least a Grade 10 or equivalent literacy level to cope with the course content and instructions
- **Mining experience:** It was clear that the individuals with underground mining experience followed the content and instructions a lot better than those without experience; and
- **Computer and technology exposure:** Individuals need a basic level of computer and technology exposure to navigate through the LMS and VR headset.

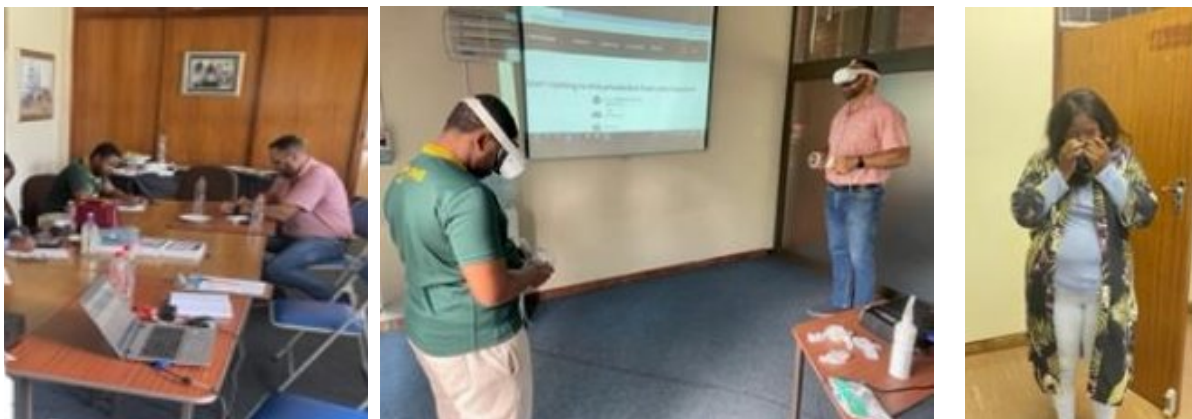


Figure 6. Pilot study participation.

Implementation of competency-based training for mine emergency response

The multi-modal competency-based training can be completed in a single day and can be offered at the Kloppersbos facility or at the mine's training centre. However, access to SCSR devices, Expectation trainers, and VR headsets will be required for the related simulations. The cost of the training will be comparable to the current mandatory annual mine fire and explosion safety awareness training.

Certificates of competence will be provided upon successful completion of all the training components, including assessments.

CONCLUSION AND RECOMMENDATIONS

The multi-modal competency-based training approach is a transformative solution to safety challenges in the SAMI, where workers face high-risk environments daily. This approach is particularly effective in preparing personnel for high-consequence, low-frequency scenarios – such as underground rockfalls, methane explosions, and machinery-related incidents – by immersing learners in realistic, high-pressure training environments that develop critical decision-making skills, risk awareness, and emergency response capabilities. The high level of learner engagement results in improved efficiency in terms of learning outcomes achieved vs investment in training time and money. It is also expected that improved retention of learning content will be achieved, although this could not be measured within the timeframe of the pilot study. It is expected that this immersive and experiential training approach will improve learning outcomes, and lead to improved safety of mine workers in South Africa.

Key safety benefits of multi-modal competency-based training in the SAMI include:

- Improved training outcomes when compared to conventional lecture-based training
- Reduction in workplace fatalities and injuries
- Improved hazard recognition and risk mitigation
- Greater knowledge retention, recall and practical application; and
- Alignment with regulatory and industry safety standards, such as the Mine Health and Safety Act.

To drive measurable safety improvements across the South African mining sector, it is recommended that this multi-modal competency-based training approach be systematically implemented across all mining operations. By adopting cutting-edge training methodologies, the South African mining industry can achieve higher safety performance, lower incident rates, and a more resilient workforce, ultimately saving lives and fostering a sustainable mining environment. The CSIR developed the competency-based training in mine emergency response to address a confirmed gap in emergency response and self-rescue training in the SAMI. The CSIR can develop similar multi-modal competency-based training solutions to suit the specific training needs of the user.

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Sustainable adoption of technology: A people-centric approach within the South African mining industry

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Understanding and clarifying the critical success factors (CSFs) that either support or inhibit the sustainable adoption of technological solutions, is required to improve the maturity of change leadership in the South African mining industry's (SAMI) modernisation journey. Technology is seen as an enabler for solving the everyday problems of multiple stakeholders within the mining value chain. Previous work has been conducted in the Successful Application of Technologies Centred Around People (SATCAP) programme of the Mandela Mining Precinct and at the Gordon Institute of Business Science towards demystifying these CSFs, which leads to the successful design, selection and diffusion of technologies within the context of modernisation. The technologies deployed in the SAMI's operations must be purposeful and ready to serve the industry's multiple stakeholders' needs and realities. The diffusion process should be people-centric, facilitating upskilling and reskilling, as skills transformation is required for the sustainable adoption of technological solutions. Mature change leadership is needed and practised intentionally and systemically; this approach will ensure that the diffused technologies achieve their purpose, namely value creation. Considering the CSFs within a people-centric change approach will accelerate the SAMI's modernisation journey, and leverage technology as an enabler of change. The sustainable adoption and diffusion of purposeful technologies as the means will accelerate the SAMI's various stakeholders into a modernised world of work.

Keywords: Change leadership, change management, critical success factors, decision to adopt, diffusion of technology, modernisation, operational readiness

INTRODUCTION

Staying competitive amid constant turbulence and disruption is a big challenge for business leaders. At the same time, capability is needed to stay ahead of change, and leading the change, as noted by Kotter (2012). The South African mining industry (SAMI) is grappling with the impact of constant turbulence and disruption and economic challenges on production levels, profitability, and sustainability. These turbulent factors include volatile exchange rates, high inflation, and frequent power outages due to the country's persistent energy crisis and electricity costs, which have increased by 12.8% year-over-year in early 2024 (Lourens, 2024). The global mining industry has also experienced dampened commodity prices, with decreased economic growth and demand in platinum group metals due to growing demand for electric vehicles. Apart from external economic and infrastructure pressures, business operations in the SAMI are experiencing operational challenges and declining resource grades, resulting in deeper underground mining operations and a spike towards higher operational costs.

The flip side of the coin is the need for critical minerals, providing the substantial opportunity to be the supplier for the global just energy transition. Critical minerals are further essential for the functioning of modern technologies. However, the critical minerals supply chain is at risk as the worldwide demand to meet net-zero and sustainable development goals increases (Dou *et al.*, 2023).

The SAMI's commitment to modernisation

Despite these challenges, the SAMI remains a key contributor to the mining and minerals value chain – a strategic pillar of the South African economy, and a significant source of employment. As reported by the Minerals Council South Africa (Baxter, 2023). In 2023, the SAMI employed 479 228 people, contributed R85.8 billion in taxes and added R444.2 billion to the country's gross domestic product (GDP) (Lourens, 2024). In the quest to remain competitive and respond to the demands, Rodger Baxter highlights the required changes. He states that digital transformation is imperative and a key enabler for the mining industry to achieve its business value drivers. These drivers include enhancing safety, health, security, production volumes, workforce, and leadership capability. In the case of the SAMI, the digital transformation journey will require bespoke innovations that will address old mining infrastructure through retrofitting and interoperability (Baxter, 2023). Statistics released by the Minerals Council (2023), revealed that the mining industry is one of very few sectors in South Africa that is adding jobs in the prevailing economic climate. The sector created 15 500 more jobs in 2022, lifting total employment to 475 560 in the sector (Minerals Council South Africa, 2023).

The SAMI has embarked on a modernisation journey that is defined as “a process of transition and transformation of the mining industry of yesteryear and today to that of tomorrow” (Minerals Council South Africa, 2021). A partnership was established between the Minerals Council of South Africa (MCSA), the Department of Trade and Industry (DTI), the Centre for Science and Innovation (CSIR) and Mining Companies to bring about change in the technological space and modernise the industry (Le Roux, 2021). A report presented by the World Economic Forum and Accenture in 2017 calls for urgent action to SAMI and provides a big opportunity for modernisation as imperative for leadership. The sustainable adoption of various technological solutions is seen as the enabler of unlocking value. The report explains that digital technologies can help South African mining businesses unlock ZAR153 billion in value by 2026, about 51% of the current mining size. This will increase the mining sector's contribution to GDP by 2%. Other benefits include increased output, reduced personnel costs, improved asset utilisation, reduced downtime, and fewer health and safety incidents (Macnamara, 2023).

Modernisation is closely associated with concepts such as the fourth industrial revolution (4IR) as popularised by Schwab (2016) who was the founder and chairperson of the World Economic Forum. The concept of modernisation, and specifically 4IR, would alter the way we conduct work. The impact of 4IR in the mining industry has already changed the face of mining as mining companies demand the supply of internet of things (IoT) services to enable underground self-guided vehicles (Bechtsis *et al.*, 2017), sustainable green solutions in the supply chain (Majerova and Das, 2023) and improved modelling, data analytics and monitoring (Ghorbani *et al.*, 2023). Besides the technological impact on our work context, Schwab (2016) provides thoughtful insights, and states that 4IR has enabled new physical possibilities. IoT combines physical and digital applications, referring to cars, houses, and hotels. Automation will bring prosperity and create new jobs, but it also impacts public institutions, as the public voice can be expressed and act with or against government systems, challenging top-down approaches to regulations. Modernisation of the mining industry may involve mechanisation and automation and is considered the path that will change processes, technologies, skill sets, and the social and environmental impacts associated with current mining practices (Singh, 2017).

Positive triggers for change

Zulu *et al.* (2021) encourage the mining industry to leverage these positive triggers when introducing technologies. Technology acceptance, adoption and diffusion can create value by enhancing worker safety, increasing cost and process efficiency, achieving environmental sustainability and enabling data-driven decision-making. The opportunity therefore exists to extend the longevity of our industry and the benefit of strengthening the value chain. Ntsoelengoe (2021) highlights that “the modern mine will have to act nimbly in integrating advanced technologies into every step of the value chain – from

detecting and exploring minerals, to advanced extraction and real-time digitalised procedures overseen by an empowered workforce. The buzzwords 'digitalisation' and 'people-centred modernisation' have also been adopted in this sector. The term 'Industry 5.0' was coined to represent a new phase of industrialisation and builds on the technological advances of Industry 4.0. The stronger focus on human centricity, sustainability, resilience, personalisation and customisation, and bioeconomy was identified in the scoping study completed by Müller and van Dyk (2024) and presented as the shift of human-machine collaboration, indicating a focus from economic value to societal value and well-being. The shift towards sustainability in the adoption of technology requires a people-centric approach to change leadership, as proposed by Botha *et al.* (2024).

Despite this positive push, the SAMI's technology adoption and diffusion rate remains significantly below expectations. These technologies also do not generate value. Macnamara (2023) refers to the dismal findings mentioned at the Electra Mining Africa Expo 2022 by Motilal, and noted that digitalisation adoption has been low, slow and fragmented in the SAMI. The opportunity presented by Accenture and World Economic Forum (2017) to unlock value will not be realised as current skill shortages are evident in advanced analytics needed to fast-track the unlocking of the potential value in digitalisation. If technology diffusion and adoption stay low, the potential for value creation of multiple stakeholders will continue to be elusive, and the modernisation journey will fail to be purposeful. Business leaders should leverage these positive triggers as the expectation for sustainable mining practices increases. The need for change is clear, and the opportunity is looming. How we respond depends on who we are and our level of maturity to practise change leadership within a modernised context.

The SAMI has reacted positively and placed people-centred change management at the core of the modernisation process, as it is believed that a holistic approach is desirable for modernisation initiatives to serve this purpose (MCSA, 2019). The people-centred approach is envisaged within the context of the fourth (and almost the fifth) industrial revolution. It is driven by the SATCAP research program, seeking to understand how people relate to each other and with technology in this process of modernisation. Through the SATCAP program at the SAMERDI research unit, the quest for people-centred design is advocated, exploring the social agenda of modernisation, states Ramparsad, the SATCAP program leader (Le Roux, 2021). The SATCAP research conducted by Stanz *et al.* (2020) shared the importance of change management as it can enable the adoption of new technologies. Still, the ineffective implementation thereof may contribute to hindrances or inhibit acceptance. Ineffective change management creates further resistance and lack of trust, instead of enabling mining companies in their journey to modernisation (Stanz *et al.*, 2020).

People-centric change leadership

Kotter (2012) refers to accelerators needed for organisational transformation, introducing a new dual system, a strategy process - such as the SAMI's modernisation journey or the technology decision and the technical diffusion process - and then a strategy network of change leaders. This dual network system will work in symbiosis to drive value creation. The change network will be doing the strategic change leadership work and leading the change management process. While the strategic network will deal with the modernisation and technology roadmap, Carreño (2024) noted this need to modernise traditional change leadership approaches and recommended including a more continuous and iterative approach to change, reflecting the agile and lean methodologies instead of a linear approach. Müller *et al.* (2019) advised that the SAMI required a more modern and exponential approach to change management when reflecting on the traditional practices employed in the SATCAP programme's initial research programs. The participative employee-driven approach is now advocated as it is evident that leading transformation requires inspiring others, communicating effectively, and motivating the organisation to adopt and internalise new behaviours (Botha *et al.*, 2023 and 2024). Sustainable adoption will be achieved by internalising new behaviours and practising people-centric change when deciding on and diffusing technologies. Kotter (2012) advises that adopting change leadership principles will produce movement and inspire change, speak to the reason and the heart, explain the why and want to, enabling a push through barriers. Change leadership will further include the collective to reduce the obstructive view.

This paper aims to clarify how people-centred change leadership would accelerate the sustainable adoption of technological solutions. People-centred change leadership is seen to identify the strategic and contextual realities and infer the CSFs to be considered to accelerate the sustainable adoption and diffusion of purposeful technologies within the SAMI's modernisation journey and value chain. It also explains how leaders can leverage these CSFs in developing a systemic, yet iterative change journey and create value by adopting people-centric change leadership principles, methodologies, and practices for technology adoption and diffusion. The goal is to encourage mining operations to move beyond focusing on technology adoption but accelerate towards technology diffusion and value creation for multiple stakeholders in the value chain. Ultimately, the intent is to facilitate a shift in behaviour among leaders, helping them to practise people-centred change leadership to diffuse technology as a means towards modernisation and value creation, rather than an end goal. This paper will reflect on the previous work in the SATCAP program at the Mandela Mining Precinct and the GIBS. The focus is on understanding the inhibitors and associated CSFs identified in documented studies (Botha *et al.*, 2023 and 2024; Ntsoelengoe, 2019; Stanz *et al.*, 2020) and strengthen the understanding through the SATCAP researchers' explorative field work. Key insights will be consolidated and presented to enhance the knowledge of change leadership and change management practices within this context.

RESEARCH METHOD

This research entailed exploratory study that focused on a discovery approach, which included determining the influencing factors found in literature about the research topic, collecting data from participants and inferring a model based on the research findings (Saunders and Lewis, 2018). According to Soiferman (2010), this approach supports the qualitative research method, which is considered a rigorous method for exploring the relevant research factors in depth. According to Saunders and Lewis (2018), exploratory research aims to pursue new insights and assess topics from a new perspective. An inductive exploratory approach was selected as no specific framework was evident in the literature against which to test the acceptance of technology solutions in the mining industry. Creswell (2003) argues that when research focuses on the 'what' question, like this current research, it is recommended that it be conducted as exploratory research due to the flexibility this provides and its ability to acquire in-depth answers to the research question posed.

Research question

The research aimed to answer the principal research question: What are the CSFs to be considered for the adoption of new technologies?

Research aim

The research aimed to understand the inhibitors and enablers which influence decision makers in mining companies to commit to adopt and implement technology solutions across the mining value chain. The research further aims to consider the various inhibitors and enablers to inform a change management blueprint through the inclusion of relevant CSFs during the conceptualisation phase and then throughout the change management process. The questions posed aim to explore the system in which South African mining companies operate and to understand the factors that influence the sustainable adoption of technology-based solutions across the mining industry. Research questions were designed to explore factors that enable and inhibit technology adoption in the SAMI.

LITERATURE REVIEW

Definitions

To contextualise the process of technology adoption and diffusion within modernisation journey, the following definitions are relevant:

- **Technology** refers to devices and systems used to solve real-world problems (Andersson *et al.*, 2016). In a general sense, we define technology as the invention, design, or discovery of something

that serves a particular purpose from a purely materialistic standpoint without needing humankind to be responsible (Carroll, 2017).

- **A people-centric approach** is a design that includes impact assessments in the field of environmental, social and governance (ESG), which are done together with a change management blueprint to be used to adopt modern technologies (MMP, 2023).
- **Technology readiness** is society's propensity to accept and use new technologies at home and work to achieve goals (Parasuraman, 2000).
- **Sustainable adoption** in the SAMI modernisation context can be defined as 'Being accountable for decisions to adopt technology, leading and enabling the diffusion process, and accelerating value realisation for the multiple stakeholders in the value chain' (own definition).
- **Change management** is defined as "the process of continually renewing an organisation's direction, structure, and capabilities to serve the ever-changing needs of external and internal customers" Moran and Brightman (2000) and at a project level "The application of processes and tools to manage the people side of change from a current state to a new future state so that the desired results of the change are achieved" (Hiatt and Creasey, 2012).

Characteristics of sustainable adoption

Adoption can be defined as an act of taking up ownership of an object or entity (Ghazizadeh *et al.*, 2011). Lozano (2022) states that sustainability, in the context of successful change management, refers to the ability to maintain and continuously improve upon the changes implemented within an organisation over the long term. It involves ensuring that the benefits of the change are enduring, and that the organisation does not revert to old practices once the initial change efforts are completed. This requires planning for the change management work to be done to institutionalise the practice or even improve it. Sustainability transformation seeks to create long-term value for a business or organisation while considering ESG practices (Sancak 2023). Sustainable adoption can therefore be explained as taking ownership of the decision to adopt the implementation process and the impact of deploying a technology, to see it through and derive the value of the technology. The sustainable adoption of technologies embodies the zero-harm mindset of SAMI. It aligns with the findings of Trawick and Carraher (2023), who attributed the success of sustainable adoption to the integrative approach used and the resulting value derived from implementing these technologies.

Inhibitors and enablers for technology adoption

Ntsoelengoe (2019) identified inhibitors and enablers impacting technology adoption in the SAMI and informing what to plan for during the change process. The unit of analysis selected was the decision-makers in the SAMI, executives, senior managers, and senior operational managers who are directly involved with introducing innovative technology solutions to their business. Table 1 reflects on these factors that inhibit the adoption of technology solutions in the SAMI.

Table 1. Factors which inhibit the adoption of technology in mining (Ntsoelengoe, 2019)

Inhibitors	Details of factors that prevent technology acceptance
Low technology readiness levels*	There was low impetus from mining companies to accept low readiness level technology, which was associated with high risk of introducing an unproven technology into an operational business value chain.
Capital funding	This pertains to the lack of funding, a definite inhibitor for introducing technology solutions in the mining environment.
Digital skills	The lack of required digital skills necessary for executing technology functions. Relevant digital skills such as computer, engineering, chemical, analytics and coding as part of preparing for the fourth industrial revolution and adopting technology solutions.
Behavioural change	The individuals' mindsets and perceptions about the benefits of technology solutions. Technological change influences social and behavioural changes, and acceptance will fail if the individuals' behaviour does not change.

*Low technology readiness levels in this context refers to the technology's maturity level.

The enabling factors were defined as those that make it possible for decision-makers to adopt the technological solutions, thereby supporting the adoption of modernisation. These factors are presented in Table 2.

Table 2. Factors which enable the adoption of technology in mining (Ntsoelengoe, 2019)

Enabling factors	Details of the factors
Research and development	Research and development were required to develop appropriate technology solutions, which involved testing, developing, and demonstrating that a technology solution was suitable for providing the solution.
Funds dedicated for modernisation	Most respondents agreed that capital funding was an essential part of modernisation and that funds dedicated to technology adoption enable the investigation of appropriate technologies to drive value for the business.
Information systems (IS) infrastructure	Some of the respondents highlighted the importance of having the enabling information systems infrastructure necessary for equipment communication and successful utilisation of technology solutions.
Organisational culture	Innovative culture that enables a collaborative environment where information is shared and where employees are encouraged to discuss their ideas.
Business ethics	Some respondents mentioned that mining companies were expected to demonstrate ethical conduct.

The inhibitors and enablers presented in Tables 1 and 2 are a combination of strategic, organisational, and human factors, and the effectiveness of the change network. Pelders and Schutte (2021) focussed on barriers (inhibitors) and facilitators (enablers) of technologies in mining, as presented in Table 3.

Table 3. Barriers and facilitators to successful implementation of new technologies (Pelders and Schutte, 2021)

Barriers (inhibitors)	Facilitators (enablers)
Premature application of technology Initially high or unexpected costs Employee attitudes or resistance to change Fear of job loss as a result of the technology Suspicion of management motives Poorly engineered work systems Technical failures Poor ergonomics Inadequate human-machine interface design Inadequate training or skills New health and safety risks created Poor implementation, planning and control Difficult mining conditions	Optimal design of equipment Human-system integration Technology appropriate to work system Technology maturity Usability Operator acceptance Knowledge transfer Training and support Communication and coordination Ownership of the technology or work system by the workforce Worker involvement Trust in the technology Quantified benefits Common vision

The factors in Tables 1, 2 and 3 reflect organisational factors and technology factors but also aspects of human factors which inhibit or motivate technology adoption. During the decision-making phase, the planning to display mature change leadership and initiate the change management process will have to identify the risk of these factors and mitigate the plans

Human Factors as inhibitors or enablers

Human hardwiring

Adoption decisions are driven by human factors, being impacted by the inhibitors and enablers, and described as our tendency to accept or resist change. The concept of resistance is explained by Kotter (2012) as operating from a survival mindset. The identified inhibitors and enablers can either activate the survive or thrive channel in decision-makers, as explained by Kotter (2012), and demystify what the CSFs should be. Sustainable adoption should act as an accelerator for modernisation and be considered when crafting a change leadership and change management plan. A people-centric approach can

capitalise on the opportunity provided by human nature, to not only resist change but to also be opportunity-seeking. Moderate survival levels keep people alert, but inflated survival impacts opportunity-seeking through an activated thriving channel.

Attitude towards using technology

Attitude towards using technology (ATUT) is a person's overall affective response towards using a chosen technology (Venkatesh *et al.*, 2003). The ATUT level can be negatively triggered if the perception is created that introducing the technology might exacerbate the risk in the specific environment. One can infer that the external changes might be outpacing our internal ability. Sustainable adoption, therefore, will have to move the industry from a survival paradigm (and be a hostage of the past) towards one that thrives because of the intentional focus on providing change leadership.

Performance expectancy

The decision to adopt based on "the degree to which an individual believes that using the system (technology) will help him or her to attain gains in job performance" (Venkatesh *et al.*, 2003). If decision makers do not see the benefit of using a technology and as a result, can perform better, the performance expectancy remains low and the behaviour (to adopt or not to adopt) remains undesirable.

Technology readiness (people)

Typical technologies being adopted during the period of 4IR, also known as Industry 4.0, include technological advancements in wireless technologies, robotics, quantum computing to analyse big data, 3D printing, artificial intelligence and nanotechnology (Ayentimi and Burgess, 2019). Adopting digital transformation is among the top ten megatrends expected to impact the business ecosystem, comprising business, government, society and culture (Ernst and Young, 2015). Technology readiness studies in various industries as guided by Parasuraman and Colby (2015), attribute the propensity to accept technology to a person-centric set of generic factors perceptions are explained within the classifications in Table 4.

Table 4. Technology readiness dimensions (Parasuraman and Colby, 2015)

Dimension	Sensemaking	Impact
Optimism	A positive view of technology and a belief that it offers people increased control, flexibility, and efficiency in their lives	Motivator
Innovativeness	A tendency to be a technology pioneer and thought leader	Motivator
Discomfort	A perceived lack of control over technology and a feeling of being overwhelmed by it	Inhibitor
Insecurity	Distrust of technology stems from scepticism about its ability to work appropriately and concerns about its potentially harmful consequences.	Inhibitor

Technology readiness represents a gestalt of mental motivators and inhibitors that collectively determine a person's predisposition to use new technologies and can be measured. Technology readiness is seen as an individual-level characteristic; it does not vary in the short term and does not change suddenly when exposed to a stimulus. Higher readiness levels are correlated with higher adoption rates of cutting-edge technology and more intense usage of technology with greater perceived ease in doing so (Parasuraman and Colby, 2015). Interventions for technology adoption will benefit to reinforce the motivators and reduce the presence of the inhibitor.

Technological readiness is measured through frameworks like the TRI 2.0, and it assesses two positive motivators—optimism and innovativeness—and two negative inhibitors—discomfort and insecurity. The TRI 2.0 is an indicator to measure technology-related behavioural intentions regarding technology adoption (Parasuraman and Colby, 2015). The introduction of technology will have different impacts on different people. The change management approach should make provision for the various levels of individual readiness of either the leaders or the team members, strengthening the importance of adopting a people-centric approach when introducing technology.

Kirrane *et al.* (2016) identified factors that influence readiness as being perceived management support, organisational, situational or psychological factors. Choi and Ruona (2011) explored the psychological conditions for individuals to be ready for planned organisational change; readiness is attributed to individuals experiencing a culture of learning, whose beliefs are altered about the necessity of the change and the likelihood of its success.

Leader readiness

Singh (2017) made it clear that the people in the mining industry must change to secure sustainable business, but a positive change does require the leaders to change the realities of the industry. This can be interpreted as being cautious of “too much talk and not enough action”. “The capacity to lead change, will be the key requirement for mining modernisation and change initiatives to deliver on the sustainability agenda” (MMP, 2023). Change initiatives in mining are, however, highly dependent on a holistic approach as any change requires employee engagement and a leadership style which includes operational levels in decisions, as stated by Bezuidenhout and Schultz (2013), “If the leadership is not experienced as mature enough to enable their employees to cope with change, upheaval, and to remain engaged throughout the change process, the stability and prosperity of the organisation are in jeopardy”.

Consistent reporting, however, identified that the speed of adoption by followers at mining operational levels is far below the requirements to modernise the industry (PWC, 2023). Hermanus *et al.* (2015) previously ascribed the slow rate of technological change to the aptitude of the industry to be slow with the adoption of change initiatives, methodologies, and practices in general. The inefficiencies in leadership and a lower readiness level of leaders in the SAMI, were raised as other reasons for slower change, as innovations such as 4IR are dependent on a more modern leadership style and improved practices, as reported by Uys and Webber-Youngman (2019). Research further stated that the current dominant leadership style does not fit the new envisaged modernised mining industry. Uys and Webber-Youngman (2019) and Boloko (2018) explored perceived leaders’ inefficiencies during the change process and noted a severe lack of specific change leadership competence within the South African leadership competence repertoire. With the current perceived inefficiencies at the operational level as a backdrop, the mining industry’s future is planned for in full force, and the dependence on operational leaders for implementation is looming.

Organisational Factors

Strategy

Zulu *et al.* (2022) highlight the lack of strategy as a significant adverse driver for SAMI in modernising, and challenge leaders to become strategy drivers. To achieve the modernisation goals set by the SAMI, policymakers and leaders must adopt the principles, methodologies, and practices of human-centric design and people-centric change management to lead the value creation process intentionally and beyond. The PWC report on digital transformation in the SAMI (PWC, 2023) states that technology investment is deliberate. A focus is placed on delivering on commitments made to shareholders and communities; defining work across the mining value chain, finding, mining, treating and trading; carbon neutrality, renewable mines, improved resource and data-driven business strategies incorporating digital enablers. The focus is on measurable value creation, i.e., tracking the real-world benefits. The decision to adopt and diffuse technologies is driven by realities such as the older mines, which can struggle with digital transformation (legacy systems), and new mines, on the other hand, which are designed with digital in mind upfront. Reports on the lack of qualified resources speak to the need for upskilling and reskilling and resistance to change from the workforce, referring to the need to rethink our strategic approach to technology adoption processes (Bouckenooghe *et al.*, 2009).

Value drivers

Innovation will significantly make businesses sustainable with the impending technological revolution (Jacobs and Webber-Youngman, 2017). Various internal and external factors influence the adoption of technology solutions in the mining sector. These key value drivers, identified by Iacovou *et al.* (1995), highlight the primary benefits that encourage mining organisations to embrace technological innovations. Lane *et al.* (2015), concluded that mining companies are driven by three core business

imperatives when adopting technology: enhancing safety and health across working environments, improving efficiency and productivity to reduce costs, and promoting environmental sustainability. Despite these motivations, the decision to adopt technology has often been constrained by cost-saving measures, leading to capital restrictions – particularly in South Africa, where low profit margins have further limited investment, as Lane *et al.* (2015) noted. There is broad agreement that mining companies must take responsibility for identifying, assessing, and integrating technology solutions within their existing operational value chains. Return on capital employed is a critical metric for allocating and distributing capital to sustain business operations. However, this financial measure also challenges technology adoption, as the risks associated with selecting appropriate solutions can deter investment. The primary value drivers for adoption and determined by Lumadi *et al.* (2024) in mining are safety improvements, efficiency and productivity increases, operational cost reductions, and environmental sustainability.

Innovation decision process

Innovation adoption decisions in organisations are traditionally made by senior management, expecting employees to use the innovation ultimately. The decision-makers based on Rogers' (2010) findings, undergo an internal process referred to as the innovation-decision process. This process may lead decision-makers to adopt technology innovation, which is also defined as making complete use of it. Innovation decision has been described as a five-step process that involves decision-makers first obtaining knowledge about the innovation technology and establishing attitudes toward adopting or rejecting the innovation, followed by implementation and, lastly, confirmation of the decision. The stages of the innovation decision process are shown in Figure 1.

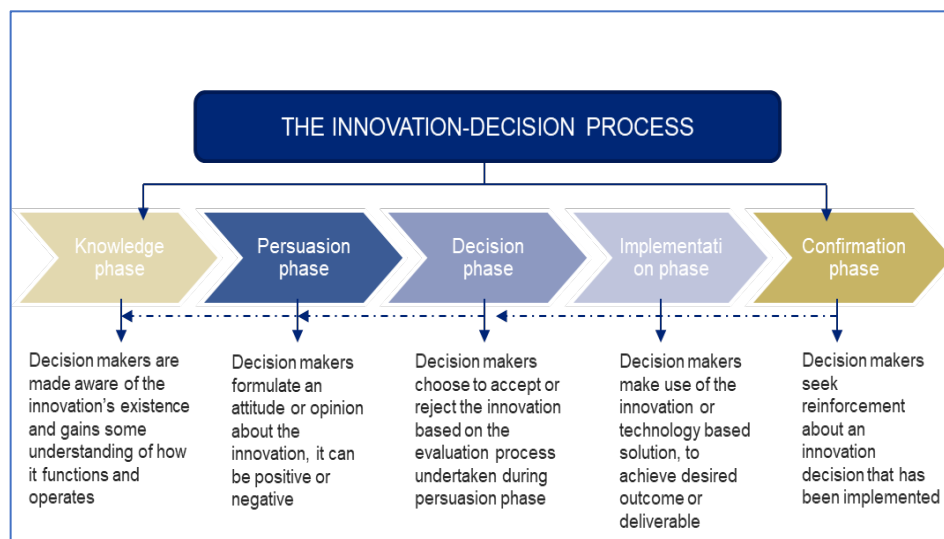


Figure 1. Innovation-Decision process (Rogers, 2010).

The main idea of the theory is that four elements influence the spread of a new idea: innovation, communication channels, time, and social system. A key observation within this process is that the decision-makers dictate and lead the innovation process and the implementation decision. The social system, key stakeholders and needs are not reflected within the model as represented above.

Mining companies in the SAMI are forced to adopt cutting-edge digital technologies and innovations to improve safe working conditions and remain competitive, efficient, and responsive to changing market conditions, including volatile commodity cycles. The adoption of technology can be understood through fundamental models like the one proposed by Iacovou *et al.* (1995), which highlights three key factors influencing adoption that are outlined below:

- **Perceived Benefits:** Mining companies drive the adoption of digital technologies when they

recognise clear advantages, such as improved safety and health, increased efficiency, cost savings, enhanced decision-making, or improved customer experience. These benefits justify investment in mine digitisation and change in company strategy.

- **Organisational Readiness:** An organisation's ability to adopt new technologies, including a digitally enabled workforce with relevant skills and know-how, digital-enabled technical infrastructure (e.g., wireless backbone), and enabling systems and processes.
- **External Pressures:** Businesses often face external pressures from competitors, customers, suppliers, regulatory bodies, and industry trends. These forces push organisations to embrace digital transformation to maintain relevance, comply with regulations, and meet market demands.

Upskilling and Reskilling

Lumadi *et al.* (2024), identified acceptance in the mining industry as being impacted by training, funding, executive sponsorship, employer-employee relations, research and development, change management and communication. Technology skills requirements were classified as either skills-biased, routine task-bias or complex task-biased. The skills requirements increase when the type of technology to be adopted moves towards complex changes. Bezuidenhout *et al.* (2021) highlight the impact of the skills revolution as it impacts the mining industry, being seen as a type of industry entering the automation sphere. The impact on jobs on manual levels is of concern as the typical manual jobs are at risk when being automated without upskilling the current workforce. The future of work is seen as becoming a reality where more complex and analytical skills will replace manual skills. The 2025 World Economic Forum job report predicts that, on average, workers can expect that two-fifths (39%) of their existing skill sets will be transformed or become outdated over the 2025-2030 period. Analytical thinking remains the most sought-after core skill among employers, and seven out of 10 companies do consider it essential in 2025. The other sought-after skills include resilience, flexibility and agility, along with leadership and social influence.

Digital literacy and competence

The SATCAP researchers consistently identified the need for digital literacy skills and competence requirements at various levels in the SAMI. The capacity to use and integrate technologies leads to proficiency and competence to provide the requisite leadership for the SAMI modernisation journey (Mahadeo *et al.*, 2022); Botha *et al.*, 2023) (Figure 2).

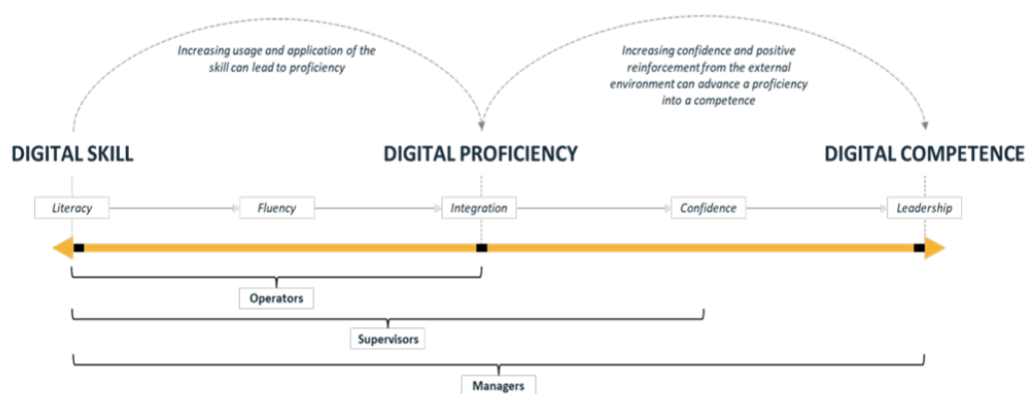


Figure 2: Digital Competence Assessment Tool for SAMI (Mahadeo *et al.*, 2022).

Sustainable adoption of technologies does require contextualising and scoping the technology, organisational and human landscape. Change leadership provides the acceleration to identify and acknowledge the inhibitors and create an enabling network of accelerators to overcome inhibitors. Mature change leadership within SAMI provides the impetus to adopt technology to create value for multiple stakeholders and consider the context and the content of the change.

FINDINGS

The SATCAP Change Management Blueprint, which is discussed in the recommendations section in detail, was applied in three South African mines in different modernisation phases. The participant mines included a modern zinc mining company, a more modernised platinum mining company and a gold mining company, involved in modernisation efforts. The Change Management Blueprint was applied before, during and after the respective adoption processes and learnings consolidated. Table 5 reflects the case study of learnings.

Table 5. Considerations prior to SATCAP Change Management Blueprint implementation (Botha et al., 2023)

Considerations	Description
Skills and training on technology	The mine operation needs to consider the skills needed, training and knowledge that is relevant for a specific technology, and if these are lacking or limited, put in place training and development plans. Upskilling, reskilling, new skills development becomes essential for new technology adoption.
Literacy levels and digital literacy	Consideration must be made of the literacy levels of the users of the specific technology. Digital literacy is key for digital transformation.
IT infrastructure and systems and funding	Sites may be willing to undertake the adoption of new technologies but there may not be sufficient information technology (IT) infrastructure (both hardware and software); or opportunity for integration with existing systems. Mine operations need to consider the technology support structures that are required for adoption of the new technology. Funding for licensing etc. must be considered.
Environmental considerations/ working conditions	It is necessary to understand the environment in which the technology will operate. Conditions such as the physical environment need to be assessed (e.g., narrow, low stopes, confined, dusty, hot, and wet working conditions). Furthermore, for example, inputting data may be cumbersome and clumsy, and if personal protective equipment is to be removed, such may create unsafe working conditions.
Unions and DMRE/ Stakeholder inclusion	Agreement, buy-in, inclusion and support are needed from all stakeholders, including unions, regulators and employees. Health and safety risks and concerns should be addressed. Lack of stakeholder engagement leads to resistance to the acceptance of the change. There may be demands for increased job levels and pay for new skills/higher skilled jobs (current job profiles do not include use of digital devices and digital literacy skills). Individual employees are also concerned that technology will track and monitor their actions with negative consequences. Compliance and regulatory issues need agreement prior to further engagement.
One-size fits all approach	Mine conditions, environments and contexts vary, so mine operations cannot use the same product/system on every mine – even shafts have different needs.
Change management process	A change management process is needed for the adoption of modern technologies. Leadership should own, drive and support change in the organisation and the technology adoption strategy.
Safety protocols	Protocols need to be updated, communicated and trained to enable safe use of technology.

The review of a shift boss logbook implementation process confirmed the importance of acknowledging the considerations identified in Table 5, and the post-implementation learnings are categorised below:

Enablers:

- Consistent application of change management and people participation throughout
- Readiness level of mine overseers as a key role player in diffusing the technology
- The decision to introduce the technology solution slowly allows for resistance to be reduced
- Good infrastructure and support system should be available
- Integrated approach with upskilling and reskilling to enable understanding and usage

- Careful consideration of hand-held units and a fit-for-purpose selection
- Risk management methodology and system defined initially, and legislative requirement included
- System is built on a set of routines and provides behavioural guidance

Inhibitors:

- Paper and technology applications are still required for legal compliance, thus running a dual system
- Management may be reverting to the old ways because of the known
- Lack of digital literacy is still a concern and influences the diffusion process

The review of implementing the SATCAP community engagement tools and the ESG integrated dashboard and learnings was recorded as presented in Table 6. The learnings inform the organisational factors considered to successfully diffuse the SATCAP tools as reported by the mining implementation project team of SATCAP work package 3.1 in 2024.

Table 6. Learnings and considerations after SATCAP community project implementation

Consideration	Description
Leaders' ambition	• Strategy execution is needed to support managerial effectiveness. • Personal agendas need to be set aside to allow for transformation. • Leaders need to lead with intent and purpose. • ESG requires a focus on social transformation. • Adopt a proactive approach. • Follow a risk-based process. • Establish communities of practices. • Provide for leader sponsorship.
Change requirements	• Change is a structured process. • Make data-driven decisions. • The data behind ESG is becoming more important. • Understand the detail of the data. • Research data needs to be actioned. • Innovation is unavoidable. • Leverage technology for community/small, medium & micro enterprise (SMME) engagement.
Organisational design and structure	• Fully competent and integrated team needed to be available. • Community liaison officers (CLOs) needed to be appointed on a contractual basis. • CLOs were trained to understand and act as change agents. • CLOs have a voice (informed) for communities and SMME. • Campaign needed to be structured. • Facilitated the input of data and information into the dashboard (source the information) is needed. • CLOs have local knowledge to facilitate knowledge sharing.
SAMI industry learnings	• SATCAP tools can be implemented – it is possible! • What we do with the information is key; this should lead to decisions. • Measure the impact year on year – develop a baseline.

RECOMMENDATIONS

Change leadership approach for the SAMI

Technology adoption and value creation can further be enabled or inhibited, depending on the change leadership approach of the diffusion process.

People-centric approach

A people-centred design approach is explained as inclusive of impact assessments in the field of the ESG, are done together with a change management blueprint to be used to adopt modern technologies

(MMP, 2023). The people-centred design practice requires designers to focus on four key aspects, namely (1) People and their context; (2) Seek to understand and solve the right problems, the root problems; (3) Understand that everything is a complex system with interconnected parts; (4) Initiate small interventions to prototype, test and refine to ensure that their solutions truly meet the needs of the people they focus on (Norman *et al.*, 2022). In guiding a people-centric approach to design and adoption, Graetz (2000) states that “against a backdrop of increasing globalisation, deregulation, the rapid pace of technological innovation, a growing knowledge workforce, and shifting social and demographic trends, few would dispute that the primary task for management today is the leadership of organisational change”. The gap to be closed should be understood by every individual ‘living’ in this outer world (MMP, 2019). Technological advancements and 4IR have at their heart the stakeholder principle, and leaders will be required to ensure that the benefits of transformation are as much a public good as a private gain. The SAMI’s modernisation efforts will, therefore, be as much a design effort as an adoption effort to lead the change with people moving centre-stage.

Human-centred design

Adopting human-centred design (HCD) aims to create value by viewing people as collaborators and enhancing their role by placing more importance on human intelligence. The focus is on upskilling and reskilling workers and placing a greater responsibility on supervising the systems and reducing mundane tasks (Muller and Van Dyk, 2024). Including stakeholders is related to the successful adoption of new technologies associated with modernisation, and people-centric design processes are recommended. Involving users in all stages of technology development has social and economic benefits (ISO 9241-210, 2010). HCD is “an approach to interactive systems development that aims to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors/ergonomics, and usability knowledge and techniques. This approach enhances effectiveness and efficiency, improves human well-being, user satisfaction, accessibility and sustainability; and counteracts possible adverse effects of use on human health, safety and performance.” The HCD process is iterative, and includes the following steps (ISO 9242:210, 2019):

- Plan the human-centred design process
- Understand and specify the context of use
- Specify the user requirements
- Produce design solutions
- Evaluate the design

Adopting a stakeholder principle

Schwab (2016) advises that 4IR has at its heart the stakeholder principle and leaders will be required to ensure that the benefits of transformation are as much a public good as a private gain. Marwala *et al.* (2017) explains that the economic law of supply and demand is a fundamental law of economic trade, where the demand determines the price. If the supplier is not willing or cannot supply at the acceptable price, there is no trade. Therefore, as the context of mining changes, the demands on leaders will change, or there will be no trade. Modernisation in the mining industry embraces the stakeholder principle, and co-creation in identifying needs and designing solutions is encouraged (MMP, 2023). Pelders and Schutte (2021) noted that worker participation in equipment development can improve user acceptance and product quality. Workers from all organisational levels in mines were reported to be excluded from equipment design, and stakeholders identified barriers including the experience of workplace culture (reference made to leadership, trust, training, performance, and remuneration factors). Human-centred design approaches and independent platforms for engagement on equipment design requirements were recommended.

Enable collective change leadership

Leading change is associated with the work of Kotter and von Ameln (2019), who suggest moving from traditional change methods in technology adoption towards accelerating with leaders building networks inside organisations. Edmondson (2002) proposes that change leadership be transferred to work teams, and learning will become a function of leading change in a psychologically safe environment. The change landscape is moving from the individual to the collective and the collective

efficacy should be noted to navigate change (Bandura, 2000). Therefore, the drive for technology adoption and diffusion cannot depend on executive decisions, as the appetite for technology sometimes manifests in the middle and junior ranks. A more collective approach to leading the digitisation and modernisation journey calls for collective change leadership.

Communication with stakeholders throughout the diffusion of innovation

Rogers (2010) researched more than 508 diffusion studies and coined the 'diffusion of innovation' theory for adopting innovations among individuals and organisations. This theory explicates "the process by which an innovation is communicated through certain channels over time among the members of a social system". The well-known innovation adoption curve was conceptualised. The identification of the need of the various types of adoption was explained by Kotter (2012). Innovations are seen to prefer a challenge. Early adopters want to understand why. Early majority adopters require proof. Late majority adopters need commitment. Laggards need time.

Change management fundamentals

Change management is a relatively young discipline drawing on diverse bodies of knowledge, including psychology, behavioural science, social science, organisational development, project management, process management and neuroscience (Hiatt and Creasey, 2012). As an emerging discipline, change management focuses on those individuals affected by the change, how their adoption and proficient usage of the changes (may it be technology, practices, work cycles) affects them as individuals, but also how they do their jobs. A successful change management journey contributes to the achievement of the initiative's targeted results.

During the implementation phase of planned change, Weiner (2009) advises that the change management process should assist with the individual's readiness for change. Readiness refers to the member's shared *commitment* to implement the change and shared belief in their collective capability to do so. It can be stated as change efficacy derived from the motivators and inhibitors. When organisational readiness for change is high, organisational members are likelier to initiate change, exert more significant effort, exhibit more remarkable persistence, and display more cooperative behaviour. The result is more effective implementation. The opposite of readiness for change is resistance to change. Readiness for change within the context of the SAMI's modernisation would require commitment from all affected participants and the collective commitment. Choi (2011) identified the causes of many organisations' inability to achieve the intended results from their change efforts, as an implementation failure, not in the innovation or initiative itself. Innovation and change efforts fail because the change leaders often underestimate the central role of individuals in the change process.

Adopting a systems approach

The SAMI can accelerate its transformation journeys, whether digital technology transformation, strategy execution or culture change, if the technological adoption is being dealt with systemically. Knowing the baseline, understanding conditions and working within the stages or readiness are some of the learnings shared by Kotter (2012). Therefore, sustainable adoption of technological solutions requires considering the input (the baseline of what is happening and needs to be considered), the transformation process (what and how the technology is diffused), and the output (the value creation – did we purposefully solve the required problem), all of which feed into the new reality. A systems approach to change management involves viewing an organisation as a complex system of interrelated parts, where changes in one part can affect the whole. This approach emphasises the importance of understanding the interdependencies and interactions between different components of the organisation during the change process (Boikhutso, 2013). According to Lozano (2022), the key aspects of sustainability in change management include:

- **Long-term vision:** Establishing a clear vision for the future that aligns with the organisation's goals and values. This helps ensure that changes are implemented, supported, and maintained over time.
- **Embedment in culture:** Integrating new practices, behaviours, and attitudes into the organisational culture. This means that change becomes a part of the daily operations and mindset of the organisation, rather than being seen as a temporary initiative.

- **Continuous monitoring and improvement:** Regularly assessing the changes' progress and impact to identify improvement areas. This involves setting up feedback mechanisms, performance metrics, and regular reviews to ensure the change remains effective and relevant.
- **Adaptability:** Building the capability within the organisation to adapt to future changes and challenges. This includes fostering a culture of innovation and continuous learning and equipping employees with the skills and knowledge needed to manage change effectively.
- **Leadership and support:** Ensuring that leaders and managers remain committed to the change and provide ongoing support to their teams. This includes offering guidance, resources, and reinforcement to sustain the momentum of the change efforts.
- **Stakeholder engagement:** Keeping stakeholders engaged and informed throughout the change process and beyond. This helps to maintain their support and buy-in, which is crucial for the long-term success of the change.

Change enablement network

Recent directions in technology adoption state that change management will require nurturing an exponential mindset, “which involves unlearning much of what you’ve learned, and keeping in mind that what got you here won’t always get you where you want to go” (Finett, 2019). It is advised to move from system 1 (fast, automatic, frequent, emotional, stereotypic, subconscious) to system 2 (slow, effortful, infrequent, logical, calculating, conscious) in the way change is planned.

The implication for a change management practice in the technology adoption journey is the ability to spend more time planning for the change in system 2, to respond exponentially and have more time with people versus the technical side of the change (Kahneman, 2011). The focus of change management should, therefore, not be on following a linear approach but rather on reflecting the drive towards exponential organisations. Linear-type organisations never disrupt their own internal procedures and processes as they lack the tools, attitude and perspective to do it. It is observed that they scale and remain what they are, to do what they were built for; therefore, even the introduction of technology will result in what is referred to as “the innovator’s dilemma” (Ismail, 2014). In the exponential type of organisation, the impact (or output) is disproportionately large – at least 10x larger – compared to its peers. Because of the use of new organisational techniques that leverage accelerating technologies, they are built upon information technologies that take what was once physical in nature and dematerialise it into the digital, on-demand world (Ismail, 2014). Therefore, the world of change management can either be behind the exponential mindset or be part of the growth in the approach taken.

The requirements for exponential change management start with the manner in which we conceptualise the technology adoption process. Conceptualisation and contextualisation require disciplined thought and disciplined action to accelerate the flywheel, as explained by Collins (2024). The thought should include multiple stakeholders, value creation, collaboration, communication, people-centricity, and human-centred design. This refers to mindset and behaviours. Leaders’ actions should be strategic and intentional, aligned with the modernisation purpose and reflect the maturity and capability levels expected at a senior managerial level. With disciplined people, thought and disciplined action, the adoption process will lead to diffusion within an organisation reflecting readiness. Disciplined people refer to us, how we contextualise what we do. Thoughtful, purposeful, stakeholders in mind. Caring about the people inside and outside the business and being sensible within the realities of where we operate.

When crafting a change management journey to support the sustainable adoption of technology, centred around people, it should be intentional. When executing our plans, the focus on people-centricity and human-centred design should move to centre-stage. Current hierarchical organisational structures, designed to be reliable, repeatable and controlled, will have to work with a change network to facilitate this exponential change and be more agile, adaptable, and designed for speed (Kotter, 2012).

SATCAP Change Management Blueprint

Towards lending support to the key organisational factors, with the potential for addressing thereof, the SATCAP programme has developed a Change Management Blueprint to enable change processes

for the adoption of modern technologies, with CSFs; and an ESG Impacts Lens Dashboard, consisting of three domain-specific dashboards, noting that this includes the Change Impact Evaluation (IE) Dashboard, which considers gauging of impacts on people, organisation, and technology for the adoption modern mining technologies. The Change Management Blueprint informs the key indicators for the Change IE Dashboard.

The Change Management Blueprint is comprised of five stages, namely: prepare, plan, pilot, roll-out, and support (3PRS) (Figure 3). The blueprint consists of various Excel templates to be populated by the user. User-guidelines, templates and videos are available on the Mandela Mining Precinct website.

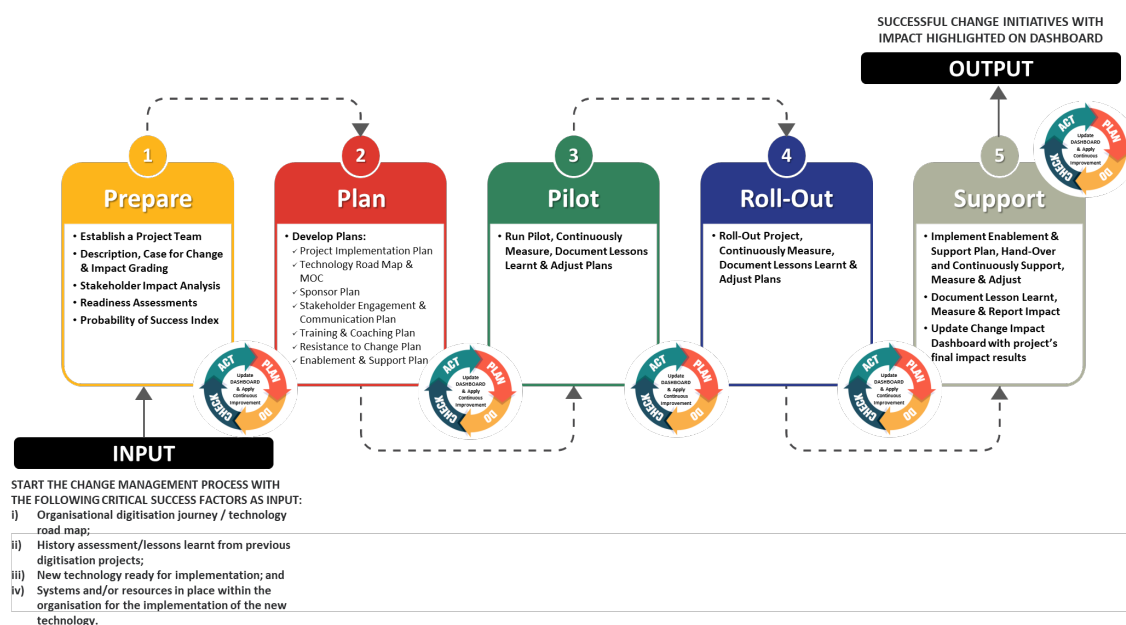


Figure 3. 3PRS Change Management Blueprint.

Critical Success Factors needed as input for a successful change management process

Field research completed through the SATCAP change management process confirms these realities and notes the importance of adopting an integrated approach to technology, process, and people readiness. The SATCAP change management research completed during the development of the Change Management Blueprint and its verification within the mining industry has identified some key factors necessary as input for successful change initiatives. The success of a change management process is influenced by the availability or confirmation of the following critical factors before the change management process starts:

- (1) The availability of the **organisation's digitisation strategy or technology roadmap** that indicates where this specific modernisation project or technology will fit in the larger strategy.
- (2) The availability of **documented lessons learnt from previous digitisation initiatives** so that the change management team can incorporate the learnings into their preparation and planning for the specific modernisation project or technology adoption initiative.
- (3) Confirmation that the **technology**, system or tool to be adopted are in fact **ready for the change management process**. The specific technology, system or tool must be ideally on Technology Readiness Level 9 before the change management project should commence.
- (4) Confirmation that any and all **support systems**, related technologies and resources needed to enable and support the specific technology, system or tool's adoption within the organisation are in place.

If any of the above critical factors are not available or confirmed before the change management process starts, then the success of the change management process will be compromised. These critical factors impact all five phases of the change management process as stated in the 3PRS Blueprint. By ensuring

that these factors are available or confirmed, it will set the change project up for success. If not available or confirmed before the project starts, then conscious decisions must be made that will impact the change management plans to reactively try to compensate, which could lead to extended timeframes, additional costs or even an unsuccessful change initiative.

Change leadership maturity CSF (5D)

Key organisational leadership factors that support or inhibit the acceptance of technological solutions for mining modernisation were identified under the following topics representing **5 Ds in change leadership maturity**. The executive decision to adopt needs to consider the factors listed in Table 7.

Table 7. The 5 Ds of change leadership maturity

Decision to adopt	<i>Leaders will make intentional decisions:</i> - To include the contextual realities of the multiple stakeholders in the mining value chain - To include the reason for adopting the specific technology in executive decision-making - To identify the value drivers with the perceived benefits and the value to be realised - Solve the multiple stakeholders population's problems and work with their realities (who do we serve, and in which priority) within the value chain - Involve careful consideration of the perceived level of readiness, referring to the level of maturity of the technology, the perceived risk and the ease of implementation - Provide for the cost implications of the technology and the effort required to research and develop (Ntsoelengoe, 2019) - Decision of selecting purposeful technologies to solve problems
Direction leadership	<i>Leaders will adopt a people-centric approach for sustainability:</i> - Mature change leaders will provide direction and set the context for adopting a people-centric approach with sustainable deliverables as an end in mind - The direction will clarify the intent of collaboration with stakeholders during the decision-making process. Collaboration requires involvement and not just consulting. Directional leadership will guide the way the diffusion process is done, facilitate collective stakeholder engagements and diffuse purposeful technologies within the social context - Seeks to create long-term value for a business or organisation while considering ESG practices (Sancak, 2023) - Moving people from 'have to' towards 'want to' and reducing the reliance on activating the "survival channel but rather moving to the thriving channel," as per Kotter (2021)
Design leadership	<i>Leaders will be designing the capacity of the organisation:</i> - Organisational structure to include a dual network of hierarchy and a change network - Integrated processes to ensure integration of technology into current business processes and routines - Communication and learning technologies to enable capability development; and - Providing an enabling social environment across the value chain to realise value for multiple stakeholders - Design for data integrity and reduction of data waste (clarify what we really need, to make purposeful decisions and who do we serve with selected solutions) - Provide for technology infrastructure and IT capabilities (Ntsoelengoe, 2019)
Developmental leadership	<i>Leaders will be developing the capacity of people to adopt the technology:</i> - The capability of the organisation for the future world of work - Skills and capacity of technology users and supporters to enable value to be derived from the technology Readiness of the organisational structure to deal with operational realities and at the same time enable technology adoption through a collaborative change network (Kotter, 2012) Readiness of the leaders to commit to adopting technology within the context of sustainable mining and in the presence of mining realities (Singh, 2017) - Leaders' readiness to display mature change leadership, provide the context for the modernisation journey, and sponsor the diffusion process Readiness of users to adopt the technology being diffused and turn the inhibitors into motivators Development of digital literacy, proficiency and competence (Mahadeo <i>et al.</i>, 2022)

Deliver leadership value	<i>Leaders will be keeping themselves accountable to deliver value:</i> • Adopt a structured change management and innovation acceptance communication methodology, enable adoption and proficiency in using technology solutions (Rogers, 2010) • Practise change leadership principles, striking a balance between execution and future visions (Kotter, 2012) • Integrate purposeful solutions to common problems throughout the value chain; and create value for the collective, not the critical few • Ensure value creation and not merely adoption of technologies (Müller and van Dyk, 2024) • Ethical practices to predict and plan for the future of jobs to mitigate the impact and risk on people's futures • Identify the value drivers first, and then carefully decide if the technology will serve the indented purpose (Lane <i>et al.</i>, 2015) • Diffuse technologies to enable change, and create a flywheel for growth (Collins, 2024)
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In the SAMI context, change management focuses beyond the project or user adoption of the technology solution but rather on the initial adoption decision (as made by senior leadership in the context of modernisation and the ESG integration) and then how to lead change to derived value across the value chain through adopting a people-centric diffusion process enabled by change methodologies and change networking capabilities. A change network is envisaged to accelerate the modernisation journey by consciously focusing on the people side of change.

Measuring the value realisation process as CSF

Executives' adoption decisions are influenced by the value drivers, the maturity of the technology, and the level of readiness of the people to whom the technology will be diffused. Enabling data-driven decisions will add to SAMI's change maturity in making decisions and providing direction in the design, development, and delivery of value. Continuous tracking of the progress throughout the adoption and diffusion process provides a communication tool to use data for change leader decisions.

A Change IE Dashboard was developed to gauge impacts relating to change as a result of the adoption of new technologies. The Change Management Blueprint was foundational for the dashboard inputs. The Change IE Dashboard was developed using Power BI software. The data sources for the dashboard include integration and links from the Change Management Blueprint and an Excel Blueprint. The Change IE Dashboard comprises sub-dashboards with 17 key indicators. The key indicators considered in the Change IE Dashboard relate to the following sub-dashboards:

- **Organisational:** aims to gauge how the technology projects are tracked in terms of impact on business processes, safety and financials.
- **Technology:** aims to gauge the level of readiness in adoption of new technology within the organisation, including leadership readiness, organisation readiness, technology readiness and policies, procedures and process readiness.
- **Change management process:** aims to assess the peoples' readiness in terms adoption of change and gauges awareness of new technology, desire for new technology, knowledge of new technology, ability to use new technology and support for new technology.
- **People:** aims to assess peoples' engagement with new technology and implementation thereof, and gauges the number of people using new technology, people using new technology versus baseline, proficiency in using new technology and peoples' satisfaction using new technology.
- **Project:** aims to gauge the level of each project implementation and success thereof in terms of planning and introduction of the new technology project in the mine environment, and measures whether the project was on time, within scope, of acceptable quality and within budget. Additionally, this group of indicators provides a summary of the success factors for successful adoption as per the Change Management Blueprint in terms of implementing the new technology and its adoption in the mines. It provides a measure of the CSFs in place to facilitate the successful adoption and assesses the level of accomplishment of the five phases for implementing the Change Management Blueprint (3PRS).

CONCLUSION

Critical success factors need to be considered when conceptualising the change impacting the adoption decision. The CSFs identified in the SATCAP Blueprint model facilitate a combination of organisational, technological and human factors integrated into a people-centric approach. The practical application of digital technologies reflects supportive and inhibiting factors.

The leadership maturity requirements are reflected through the 5D process, reflecting the critical decisions to be made by leaders on the direction, the design of an enabling structure and change network, the development of capabilities, and the delivery of the modernisation mandate. The organisational factors influencing successful adoption centre around people are observed as following this 5D pattern and should be considered as risk factors if not intentionally practised.

The integration of these systemic enablers, namely the organisational structure design, leadership capability, technology strategy, stakeholder inclusion, integration throughout the value chain, skill levels within operations, culture impacts and various readiness levels (i.e., technology, people, processes, etc.), will accelerate the value realisation process.

The process commences with the recognition of the significance of leaders in establishing the context for change, coupled with a strategic alignment. This necessitates a leadership capability to effectively shape the contribution of the intended technology as an integral aspect of the modernisation journey. Establishing the appropriate context calls for a comprehensive approach that transcends mere operational requirements, encompassing the ESG mandate and its contributions to the mining value chain. The technology strategy should be resourced through a strategic and a change network, running a dual system.

The strategic integration of technological solutions as a facilitator/enabler for sustainable mining must encapsulate the rationale, objectives, and value proposition associated with the intended technologies. If technology is deemed a strategic imperative, a structured framework to facilitate its implementation is essential.

The application of stakeholder needs necessitates the consideration of various stakeholders and the value that is both needed and provided within the strategy. Technology initiatives conventionally begin with managerial information systems (such as dashboards and data) to address the requirement for data-driven decision-making. Concurrently, it is imperative to acknowledge stakeholders at the operational level and ESG collaborators, considering their diverse needs during the selection and prioritisation of technologies. Embracing an inclusive stakeholder approach demands effective change leadership.

The sustainable adoption of technologies encompasses their integration across the entire value chain and aligns the modernisation journey with intentionally chosen technologies.

The maturity, readiness and capability levels of the organisation, technology, leadership, and team members should be clearly defined at the outset. The levels of maturity and capability elucidate the requirements for effective change management. Resource allocation for change management expertise directly correlates with these maturity, readiness and capability levels. Furthermore, the risks and potentials associated with the current operational state can be effectively balanced to ensure both survival and growth.

Realistically considering the life of mine, and the geographical context of operations, it becomes evident that such factors will influence the prioritisation of technology adoption. Fragmented adoption tends to arise when the diffusion occurs within an environment where the intended purpose of the technology lacks relevance in relation to time and location.

There is a serious need to consider the cultural ramifications of technology beyond immediate requirements and expand its influence on domains outside of the conventional scope. Substantial evidence suggests that adopting technology can facilitate skills enhancement, with each technological advancement regarded as a fundamental component of the skills development roadmap.

Assessing readiness levels for the specific technology, grounded in the technology roadmap, infrastructure, policies, procedures, and support systems, instils confidence in the adoption process. The greater the technology's readiness level, the less demanding it is to persuade individuals. Essentially, the technology promotes itself.

The people-centric approach reflects human nature in that we resist change on one hand, yet we are inquisitive and seek opportunities on the other.

Sustainable adoption necessitates leaders who exhibit disciplined thought and actions in the pursuit of modernisation. The flywheel (exponential change) is contingent upon intentional and adaptive change leadership.

Understanding and applying the recommended factors and processes is anticipated to support the sustainable adoption of technologies in the South African mining industry, the value drivers, and the ESG imperatives.

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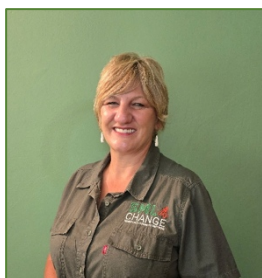
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Rina Müller (CCE)

Director
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Rina has conducted applied research within the field of change management and the mining industry's quest for upskilling and reskilling. She has a keen interest in turning research into reality through unlocking the potential of people. Rina works with her team of curriculum designers, content writers, facilitators and project leaders developing change and learning journeys within a co-created and people-centric environment. Her quest in the mining industry since 1994 is to integrate technical and behavioural approaches. Within the last 5 years, the work expanded into Africa to construct skills development journeys and move artisanal mining companies into a professionalised, modernised and mechanised world of work. Rina has served the industry in AngloGold, Gold Fields, Barplats and her consulting journey commenced in 2011. Rina is proudly a wife, mother, mother-in-law and a grandmother and resides in Potchefstroom.



Sibongile Ntsoelengoe

Executive cluster manager, mining
CSIR

Sibongile (Bongi) brings over 15 years of experience in the mining industry, with a focus on iron ore and base metal commodities. She has held several leadership positions, leading multidisciplinary teams in the development, deployment, and adoption of innovative solutions across mining operations. In her previous role as Manager: Technology at Kumba Iron Ore, Anglo American, Bongi gained extensive experience in formulating and implementing integrated innovation strategy roadmaps across the mining value chain. She currently serves as the Executive Cluster Manager for Future Production: Mining at the Council for Scientific and Industrial Research (CSIR), where she plays a key role in advancing research and innovation in support of the mining sector. Bongi remains committed to the industry through various leadership roles, including her appointment as a Non-Executive Director at Fraser Alexander and as a Council Member of the South African Institute of Mining and Metallurgy (SAIMM). She continues to provide thought leadership in developing digital capabilities and bespoke, cutting-edge solutions that enable a safer, modernised, and sustainable mining industry. Among her recent achievements is the delivery of a comprehensive research and innovation strategy roadmap at the CSIR aimed at revitalising the South African mining sector and rebuilding the mining Research, Development, and Innovation (RDI) ecosystem.



Karel Nicolaas de Kock (Nico)

CEO
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Nico is the CEO of Louis Allen Southern Africa as well as the COO Grow to N. He has been involved in Management Leadership Development and Organisational Development for over 24 years. He has impacted multiple organisation's leaders in various countries covering a wide range of industries including Mining, Manufacturing, IT, Services, Insurance and Banking. His passion lies in formulating customised Management Leadership Development solutions to address complex challenges in organisations. For an analytical person such as Nico, the Louis Allen systematic approach towards management leadership development was an ideal match. As the business has grown through the years, Nico and his business partner Neo, have added also the internationally recognised Zenger Folkman leadership development as well as the Kepner & Fourie problem-solving and decision-making offerings through the Grow to N business. Since 2014, Nico has been the country representative for The European House Ambrosetti, assisting the Italian consultancy with the coordination and hosting of various CEO forums, bilateral meetings and summits within Southern Africa. Over the last 4 years, Nico has also been a research partner for SATCAP programmes, contributing to various deliverables for the benefit of the mining industry. This ranged from supervisory leadership development to change management interventions, developing a change management blueprint and impact dashboard.



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Wessel has conducted research for both private and government institutions within the following industries: Mining, Construction, Renewable Energy, Motor Industry, Manufacturing and Production (various), Water Services, Services (Management, Delivery, Financial) and Forestry. He has taken a personal interest in investigating and understanding technology's impact on people and identifying future skills requirements. He has also operated within the educational and regulatory structures by developing Sector Skills Plans for various SETAs, developing 5-year strategies and conducting large scale skills audits. His core skill is described as developing models from academic research and applying this to real-world solutions.

The ESG impacts lens dashboard: an integration of socio-economic transformation, automation and change impact dashboards

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Mines need to have an understanding of the impacts of modernisation on people. Research has been commissioned by the Successful Application of Technologies Centred Around People (SATCAP) programme of the Mandela Mining Precinct to understand the effects of mining modernisation on people in the minerals sector, in support of the Environmental, Social and Governance (ESG) agenda.

An ESG Impacts Lens Dashboard was developed to assist mines to understand the impacts of socio-economic transformation interventions, automation, and the efficacy of change management processes in the adoption of new technologies. The ESG Impacts Lens Dashboard comprises of three underlying impact evaluation (IE) dashboards (the Socio-Economic Transformation IE Dashboard, the Automation IE Dashboard, and the Change IE Dashboard), with 19 individual sub-dashboards, and over 81 specific indicators. The dashboard was developed using a design thinking and co-creative approach and integrates into a Power BI platform. The dashboard, user-guideline, and supporting videos are available on the Mandela Mining Precinct's website. Dissemination to industry has been through various seminars, conferences and presentations at industry forums.

Keywords: Business priorities, Community engagement, Digital tools, Modernisation

INTRODUCTION

South African mines are modernising to enable improved safety, production, and sustainability. Mines need to get an understanding of the impacts of modernisation on people in mining, including the aspects of socio-economic transformation interventions, automation, and the efficacy of change management processes in the adoption of new technologies. An Environmental, Social and Governance (ESG) Impacts Lens Dashboard was developed to assist mines to understand modernisation impacts, as related to people. The development and features of this dashboard are detailed in this paper, along with preliminary findings from a case study conducted at a zinc mine.

This paper is based on work conducted for the Successful Application of Technologies Centred Around People (SATCAP) programme of the Mandela Mining Precinct. SATCAP aims to understand the effects of mining modernisation on people in the minerals sector, and lends support to the ESG agenda, with a focus on the social aspect.

The ESG Impacts Lens Dashboard is based on work conducted in three SATCAP projects in 2023, which provided insight into:

- The impact of socio-economic transformation interventions in mine host communities (Mahadeo *et al.*, 2024a; 2024c)
- The impact of automation on jobs within the mining workforce (Mahadeo *et al.*, 2024b); and
- The effectiveness of change management in the adoption of modern technologies (Botha *et al.*, 2024).

The project is built on and progresses the research conducted in the programme in the previous year (2022), which related to the development of data collection tools for mines' informed decision making. These tools included the following:

- Training Needs Assessment Tool
- Community Social Needs Assessment Tool
- Small, Medium and Micro Enterprises (SMME) Communications and Engagement Tool
- Digital Leadership Competency Gap Assessment Tool; and
- Change Management Blueprint.

The data gathering tools, as above, inform the key impact indicators in the ESG Impacts Lens Dashboard. The 2023 projects aimed to verify these tools with industry and interlink them to impact evaluation (IE) dashboards. The three related IE dashboards are integrated into the ESG Impacts Lens Dashboard to enable mines to gauge impacts around social, automation and change aspects.

REVIEW OF LITERATURE

The South African mining sector contributes 7-8% to the nation's gross domestic product (GDP) and sustains over 475 000 livelihoods, with each mine worker employed supporting approximately ten additional dependents (Minerals Council South Africa, 2023). However, the mining sector faces many challenges, such as fluctuating commodity prices, labour unrest, environmental degradation, and social conflicts (Ngobese, 2015). According to a report by McKinsey and Company (2019), the global mining industry has been under pressure due to falling commodity prices, maturing mines, declining ore grades, and increasing new-mine-development times. Modernisation becomes necessary for industry sustainability and worker safety in line with the mining industry's 'zero-harm' goal. Modernisation is a transformative pursuit with profound goals: extending mine life, generating employment, boosting exports, catalysing socio-economic development, and fostering a more sustainable and environmentally responsible mining sector (Minerals Council South Africa, 2022).

Literature suggests that the impact of modernisation on local mine communities may be evaluated according to five key drivers, as follows:

- **Economic development:** The process by which communities with a low standard of living work towards sustainable development, involving qualitative and quantitative improvements in various aspects of the economy, such as technology, productivity, and infrastructure (Market Business News, 2023).
- **Social development:** Change in the social structures and processes of a society or a group. It involves the acquisition of skills, attitudes, relationships, and behaviours that enable individuals to interact with others and function as members of society (Parke, 2020).
- **Diversity, equity, and inclusion:** A conceptual framework that promotes the fair treatment and full participation of all people, especially in the workplace or community, including populations who have historically been under-represented or subject to discrimination because of their background or identity (McKinsey and Company, 2022).
- **Good governance and best practices:** Concepts that aim to improve the quality, efficiency, and

effectiveness of an organisation or a process. They involve following ethical principles, complying with relevant laws and regulations, ensuring accountability and transparency, and engaging with stakeholders and beneficiaries (McKinsey and Company, 2022).

- **Environmental security and safety:** A concept that refers to the protection of natural resources and ecosystems from human-induced threats, such as pollution, climate change, deforestation, and overexploitation (UNEP, 2019). Environmental security and safety also imply the prevention of environmental degradation that could lead to social conflicts, violence, or instability.

The South African mining sector is undergoing a profound digital transformation, aligning with the broader global trend towards modernisation. Energy and mining companies are experiencing a paradigm shift where growth, sustainability, and technology intersect (Bain and Company, 2022). The industry recognises that increased digitisation and the swift adoption of cutting-edge technologies are pivotal for its future success. Notably, digital transformation is a driver of efficiency and a potential source of significant employment opportunities. According to projections, digitisation could lead to a net gain of more than one million jobs by 2030 (McKinsey and Company, 2018), demonstrating the transformative impact of technology on labour markets within the mining sector. This shift towards digitalisation is not merely a technological upgrade but a strategic move towards a more sustainable and prosperous economic future for South Africa (McKinsey and Company, 2018). As the mining industry embraces advanced digital technologies, it positions itself for enhanced productivity and resource efficiency and as a key player in the country's economic growth trajectory. In this context, the confluence of growth, sustainability, and technology in energy and mining companies signals a forward-looking approach that acknowledges the potential of increased digitisation to be a driving force behind South Africa's future economic prosperity. The industry's commitment to leveraging technology underscores a vision where digital transformation becomes a cornerstone for sustainable development, economic inclusivity, and job creation in the evolving landscape of South African mining.

The literature review, furthermore, informed the development of the ESG Impacts Lens Dashboard, with consideration to relevant and applicable indicators for gauging of socio-economic transformation, automation and change.

METHODS

An exploratory design process informed the development of the integrated IE dashboard. Figure 1 depicts the process that was followed.



Figure 1. Design and development methodology.

Desktop research and stakeholder engagements were conducted to gain insights relating to dashboards applied in mining and other sectors, and a background understanding relating to each of the three domain-related dashboards and indicators to consider. The Stanford Design Thinking process was used to understand and synthesise data collected. The insights from the research informed the ideation and analysis of necessary functional properties of the ESG Impacts Lens Dashboard. The dashboard draws data from the 2022 digital tools, with the SATCAP 2022 data gathering tools forming the dashboards base key indicators, which then integrates with the Microsoft Power BI Platform. The 2022 data-gathering tools provided some of the key indicators for understanding of people impacts, but this baseline was extended further. A prototype was designed and developed according to the insights, which was tested according to the needs of the mines through several validation and feedback engagements. Several iterations and refinements occurred to end up with an accepted product.

Further, to enable industry transfer, several guideline documents were developed, along with supporting videos, to ease the adoption of the ESG Impacts Lens Dashboard.

OUTPUTS

The ESG Impacts Lens Dashboard comprises three integrated domain-specific IE dashboards, with 19 individual sub-dashboards and over 81 specific indicators. The ESG Impacts Lens Dashboard indicators align with business priorities of cost, safety, people, and productivity. The ESG Impacts Lens Dashboard takes an integrated approach, collecting data through purpose-built digital tools linked with the Power BI dashboard.

The three integrated dashboards are the following:

- **Socio-Economic Transformation Impact Evaluation (SETIE) Dashboard:** Reflects the change and impact that socio-economic transformation interventions have had in mining communities through social performance indicators. It considers the impacts of social change directly attributable to mining modernisation, possible closure of mines, and support and preparation of the local communities regarding engaging in alternative economies, such as training in entrepreneurship, and the development of asset bases in communities.
- **Impact of Automation (IoA) Dashboard:** Reflects the change and impact of automation and digitalisation on the workforce within the mining operation. This dashboard considers the impacts of change directly attributable to initiatives of mines in terms of automation and digital transformation, namely the introduction of new technologies and processes, the implementation of skills and training, and changes in skills profiles and employee levels.
- **Change Impact Evaluation (CIE) Dashboard:** Reflects the effectiveness of change management practices relating to technology adoption. The CIE Dashboard specifically aims to understand the changes and impacts around people, technology, organisation, change adoption and projects, including critical success factors that should be taken into consideration when introducing new technologies for mining modernisation. This dashboard was informed by a Change Management Blueprint, which was based on Minerals Council South Africa's Mining Industry Occupational Safety and Health (MOSH) Leading Practice Adoption System (Malatji & Stewart, n.d.) and linked to Awareness, Desire, Knowledge, Ability and Reinforcement (ADKAR) principles (Prosci, n.d.).

The ESG Impacts Lens Dashboard has the following features:

- The landing page, which provides a brief explanation of the purpose of the dashboard, and links to the integrated dashboards (Figure 2)
- Instructions on how to use the dashboard (Figure 3)
- A summary of key business drivers, namely safety, cost, production and people (Figure 4)
- Summaries for the SEITI, IoA, and CIE dashboards (Figure 5 to 7)
- The SEITI Dashboard, which comprises seven sub-dashboards with 46 indicators

- The IoA Dashboard, which has three sub-dashboards with 18 indicators, and
- The CIE Dashboard, with five sub-dashboards and 17 indicators.

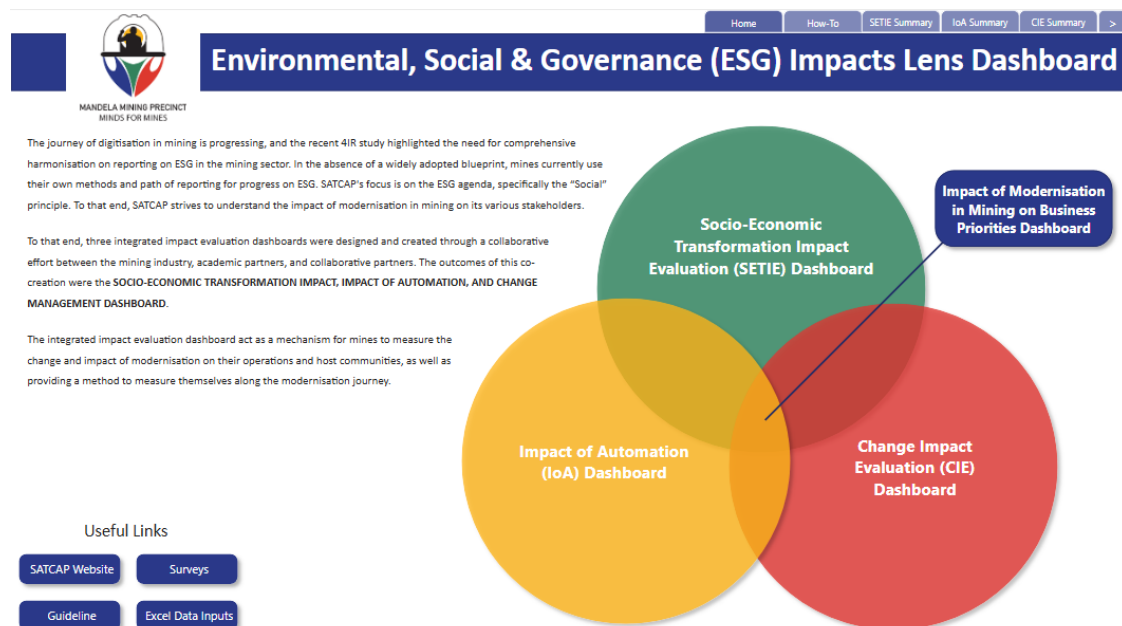


Figure 2. ESG Impacts Lens Dashboard landing page.

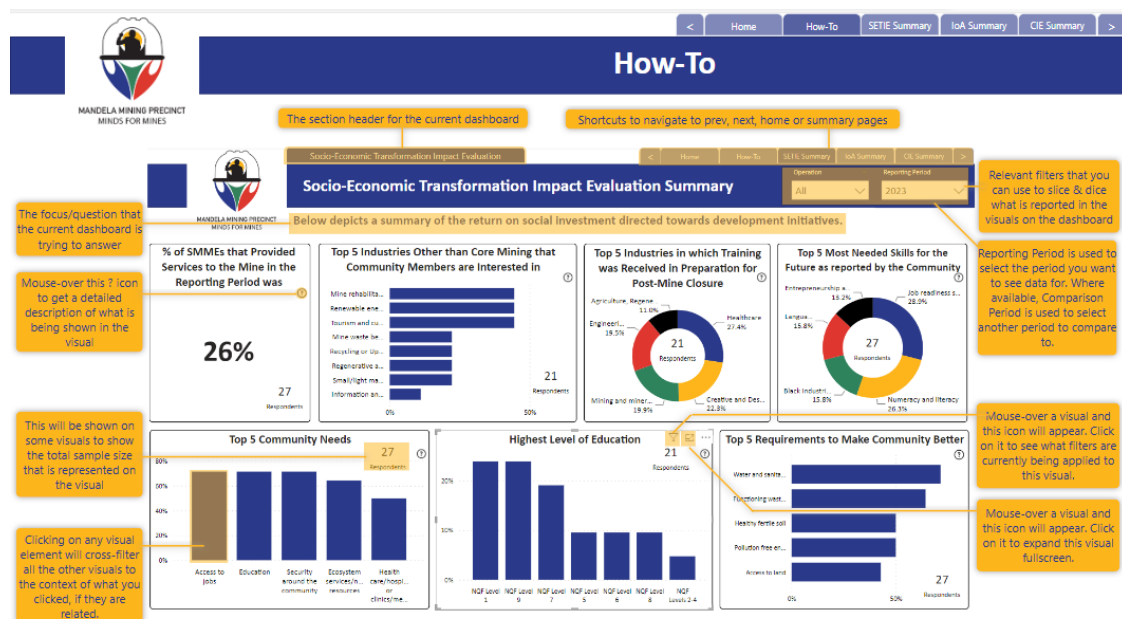


Figure 3. How-to page.

The Business Priorities Impacts summary (Figure 4) is a representation of summary data from the three domain-specific dashboards to specifically reference the impact of introducing a technology into a specific context against the following:

- **Cost:** Cost associated with technology and of training people.
- **Internal workforce (People):** Number of people in training to use the new technology, changes in employment and gender distribution, change in training methods, and the digital capability of the workforce.

- **Safety:** Number of employees removed from dangerous context, occupational health and safety (OHS) impacts due to the technology introduced (lost days, fatalities, injuries and fatigue), and the risk levels relating to the adoption of different technology projects.
- **External stakeholders** (Communities): Distribution of skills in alternate economy sectors, top five skills identified by communities for sustainable economies (post-mining), changes in the total number of community members' participation in skills-related training programmes.
- **Production:** Changes in organisation business processes to implement new technology, changes in number of automated processes in context, changes in number of projects implemented efficiently due to new technology adoption, and change in number of technology projects with change management implemented.

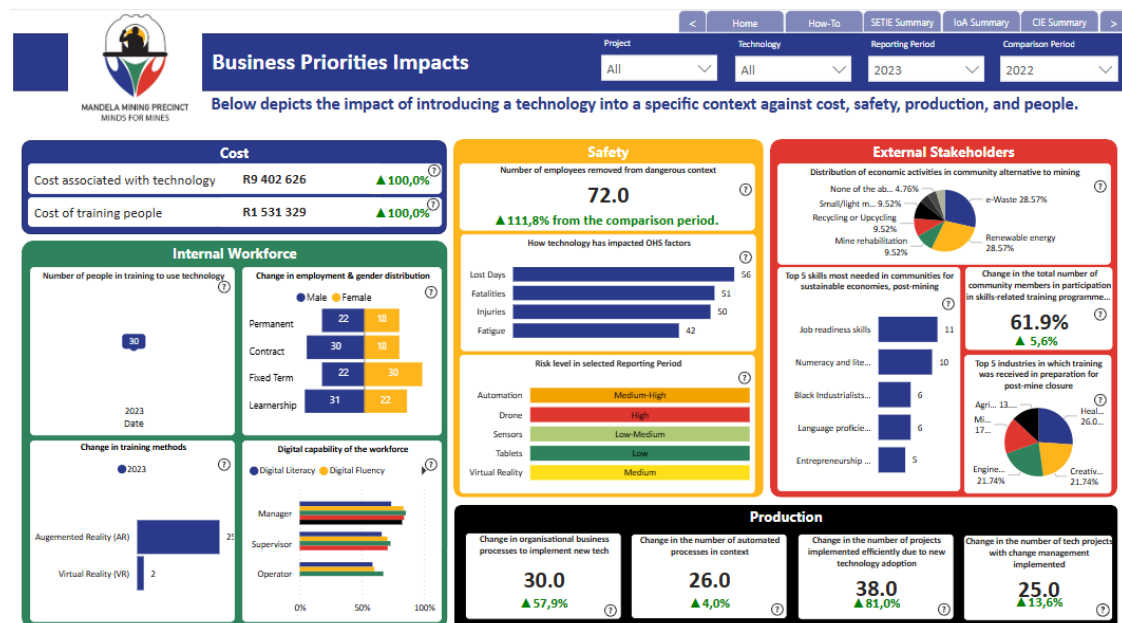


Figure 4. Business Priorities Impacts summary page.

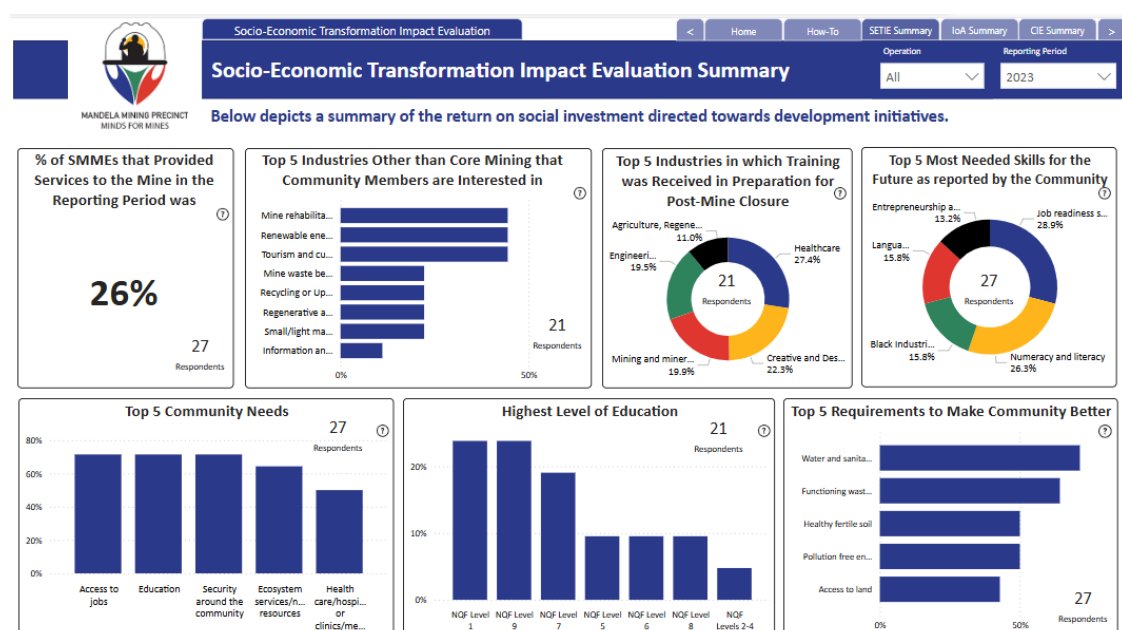


Figure 5. The SEITI summary page.

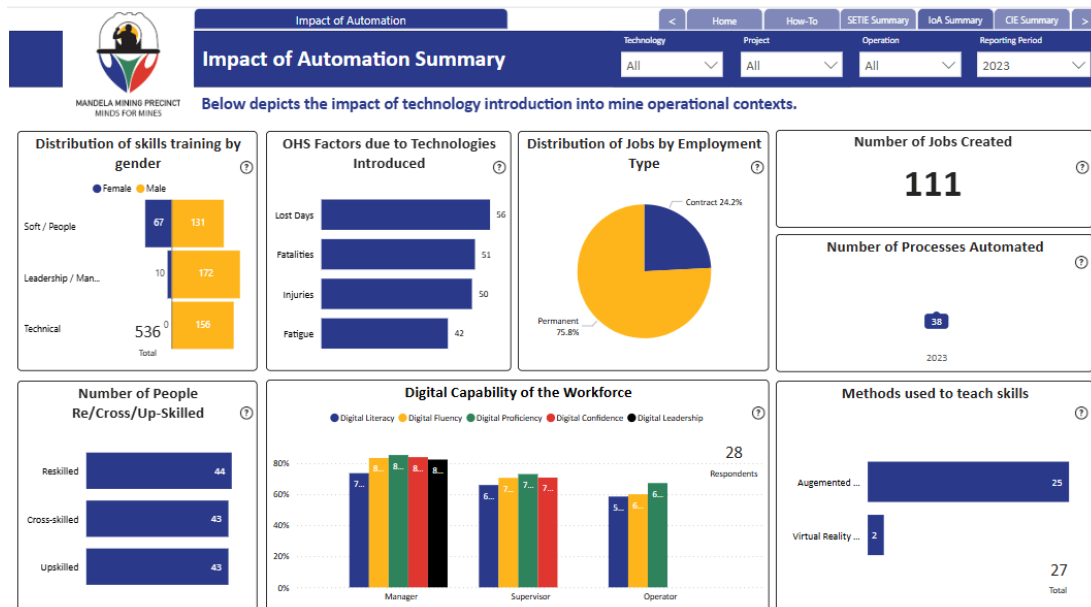


Figure 6. The IoA summary page.

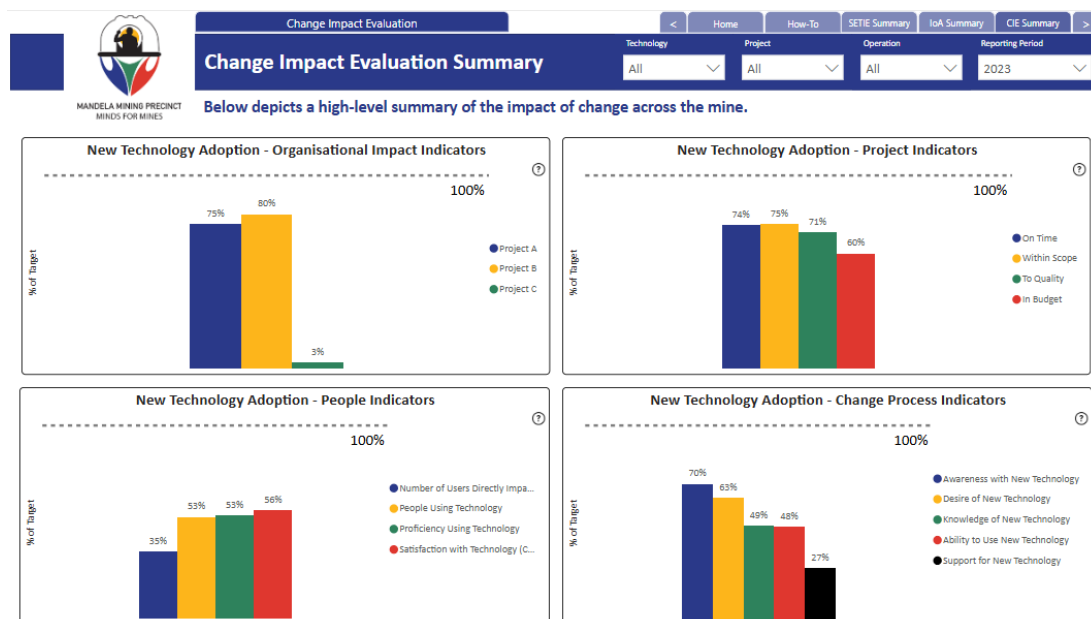


Figure 7. The CIE summary page.

The lists of indicators included in each domain-specific dashboard are shown in Tables 1 to 3. The SETIE Dashboard consists of seven sub-dashboards representing different areas including Community Skills, Community Current Needs, Community Future Needs, Community Jobs, SMME Skills and Training, SMME Information, and SMME Stakeholder Engagement (Table 1). The IoA Dashboard includes pages for the Impact on Skills and Training, Impact on jobs, and Impact on Health and Safety (Table 2). The CIE Dashboard has sub-dashboards including Organisation Impact, People and Change Adoption Impact, and Project Indicators (Table 3).

Table 1. SETI Dashboard indicators

Sub-dashboard	Indicators
Community Skills	• Highest level of education • Computer literacy • Top five skills most needed in the community • Top five skills in which training was received • Top five skills that the community is most interested in • Top five industries in which training was received in preparation for post-mine closure • Skills-related training participation in the reporting period
Community Current Needs	• Top five community needs • Top five issues affecting post-mine growth • Living conditions • Level of security • Access to education • Access to housing • Access to healthcare • Access to water • Access to food • Access to internet
Community Future Needs	• Top five most needed skills for future as reported by community • Top five businesses desired in future • Top five requirements to make the community better • Top five skills considered most important to access other job opportunities if the mine were to close • Top five skills considered most important to start your own business if the mine were to close
Community Jobs	• Of those employed, what was their employment status • Of those employed, how many work for the mine • Gender disparity in employment status • Top five alternative economy sectors in which people have skills • Top five alternative industries that people are interested in
SMME Skills and Training	• Top five skills in which SMMEs offer on-the-job training • Top five skills of importance to SMMEs • Top five industries in which SMMEs received training • Awareness of the Black Industrialist Scheme • Top five skills most needed by SMMEs for future local economies • Top five services provided by SMMEs in the community
SMME Information	• Percentage of SMMEs that provided services to the mine in reporting period • Assistance from the organisations received to grow the business • Percentage SMMEs that had easy access to loans in the reporting period • Assistance from organisations needed to grow the business post-mining • Percentage of SMMEs that have participated in related training
SMME Stakeholder Engagement	• Types of companies applying • Top five product or service offerings of companies applying • BBBEE level of companies applying • Percentage who found the application process user-friendly • Awareness of the pre-application checklist • Actively monitoring application status • Pre-application survey responses • Post-application survey responses

Table 2. IoA Dashboard indicators.

Sub-dashboard	Indicators
Employee Skills and Training	• Digital literacy score • Digital fluency score • Digital proficiency score • Digital confidence score • Digital leadership score • Number of people re/cross/upskilled • Distribution of skills training by position • Distribution of skills training by gender • Methods used to teach skills
Employee Jobs	• Total employees in the reporting period • Number of processes automated • Distribution of employees by occupation level • Distribution of jobs by employment type • Job adjustments between levels
Employee Health and Safety	• OHS factors due to technologies introduced • Number of employees removed from dangerous contexts • Change in risk level • Total reported cases of ergonomic and musculoskeletal injuries

Table 3. CIE Dashboard indicators

Sub-dashboard	Indicators
Organisation Impact	• Business process (hours saved) • Safety (lost time) • Financial results (Rands saved)
People and Change Adoption Impact	Technology Indicators: • Leadership readiness • Organisational readiness • Technology readiness • (Organisational) policies, procedures and process readiness Change Management Process Indicators: • People's awareness of the new technology • People's desire for the new technology • People's knowledge of the new technology • People's ability to use the new technology • People's support for the new technology People Indicators: • Number of people using the technology • People's proficiency in using technology • People's satisfaction with new technology
Project Indicators	• Project management (time, scope, quality, budget) • Prepare, Plan, Pilot, Roll-out and Support (3PRS) Change Management Blueprint step progression

The ESG Impacts Lens Dashboard is the visualisation output incorporating two separate data input sources. The first source is data from the digital survey tools, stored in a data Firebase project. The second source is the respective users' raw data captured and stored in an Excel workbook. Figure 8 depicts where and how to ensure success when implementing the dashboard. The effectiveness of the ESG Impacts Lens Dashboard requires synergy between four primary champions within each mine, including the Project Owner, Dashboard Administrator, Dashboard Manager, and Dashboard User. A user-guideline document provides detailed instructions that teams must follow for the data collection tools and dashboard to be useful. The dashboard, user-guideline document, and supporting videos are available on the Mandela Mining Precinct website.

Dashboard Property	Recommended Usage	Significance
Interconnectedness to SATCAP 2022 digital tools	Ensure guidelines to embed the SATCAP 2022 digital tools and link the dashboard are followed precisely.	A bespoke API was created to link the dashboard to the SATCAP 2022 tools data and automatically, in real-time, extract any data collected through the previous tools.
Google Firebase integration	Create a Google Firebase account (billing details required to setup the profile but there should be zero charged).	The SATCAP 2022 digital tools use a cloud-based database to store the data collected from the tools. An account must be established to ensure the dashboard can extract information from the previous tools.
Additional data inputs required through an Excel Workbook	Ensure the correct and accurate input of data into the Excel Workbook.	Ensuring the ESG Impact Lens Dashboard presents impactful and relevant information hinges on the accuracy of the data inputted. Keeping dashboard best practice of "garbage in, garbage out (GIGO)" top of mind.
Over 85 specific indicators	Each user should familiarise themselves with how each indicator ties into the mine's broader strategic intentions.	The dashboard provides detailed information across many specific socioeconomic transformation, automation, and change factors. The value assigned to each indicator is how the mine uses the information to inform its strategic decisions.
The primary language used is English, but tailorable	Review and translate the dashboard headings according to what works best for the specific organisation.	English may not be the predominate language within the operation. Hence, to ensure ease of interpretability the headings and subheadings can be tailored according to what works best for the specific operation.
Data outputs span across users and departments	Identify the core users who have access to the data required and ensure closer working relationships.	Multiple data inputs are required from many different sources across the mine. A key individual should be assigned from each relevant department to capture the information and work closer with the other key individuals.

Figure 8. Success factors for implementation of the ESG Impacts Lens dashboard.

PRELIMINARY CASE STUDY FINDINGS

The SATCAP digital tools were applied in a zinc mining context, to serve as a means by which needs and data can be collected from mining communities for mines' analysis and decision-making. Data gathering and validation in the mining operation were done using the Community Liaison Office within the zinc mine host community. The digital tools were deployed within the zinc mine itself. Participants completed surveys of the data collection tools, namely the Training-Needs Survey (59 responses), Community Social-Needs Survey (33 responses), and the SMME Communications and Engagement Tool (28 responses). The data analysis and interpretation process is shown in Figure 9.

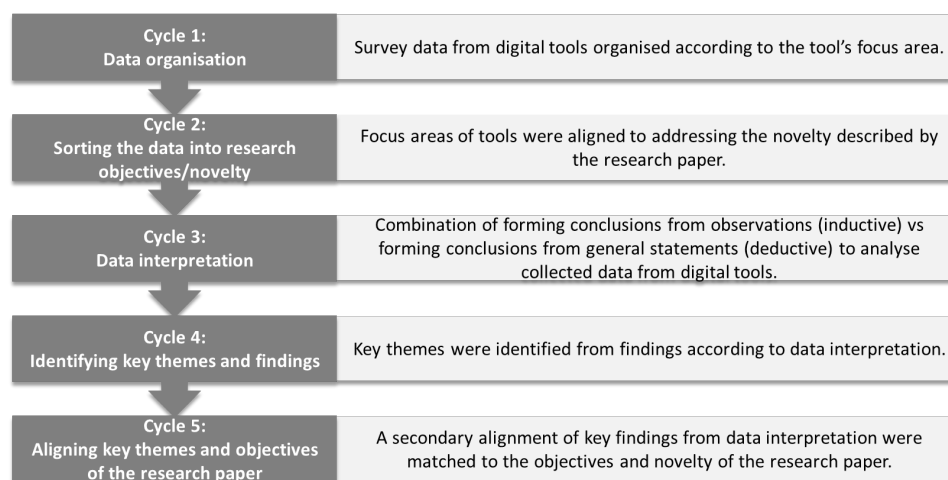


Figure 9. Data analysis and interpretation process.

Key themes from the study related to the following:

- SMMEs' present and perceived future needs
- The community's current and future social needs
- The community and SMMEs' training needs
- Alternative economists and industrialists that meet the Broad-Based Black Economic Empowerment (B-BBEE) criteria with the mine communities (i.e. Black Economic Industrialists); and
- The level of engagement between the SMMEs and the regional zinc mine.

The SATCAP digital tools provided a more detailed perspective of elements questioned within a mine's materiality assessment and may also enable more instantaneous and regular feedback with host communities. It was found that community involvement and understanding local dynamics was important when implementing digital ESG tools in the mining communities. Moreover, it was recommended that the digital tools be adapted according to the specific context and needs of a mine. Access to technological assets (e.g. smart phones or computers), internet connection, and time required to complete the surveys are further practical considerations. Findings from this study are detailed in a paper by Mahadeo *et al.*, (2024d). A follow-up study is planned for the validation of the Change Management Blueprint and Digital Leadership Competencies Tool at a zinc mine.

CONCLUSION AND RECOMMENDATIONS

An ESG Impacts Lens Dashboard was developed to assist mines to understand the impacts of socio-economic transformation interventions, automation, and the efficacy of change management processes in the adoption of modern technologies. The dashboard comprises three integrated domain-specific dashboards with 19 individual sub-dashboards, and with over 81 specific indicators. It also includes a summary of business priorities impacts, which outlines the key business drivers of safety, cost, production and people. The three domain-specific dashboards are the SETIE, IoA, and CIE dashboards. The ESG Impacts Lens Dashboard was designed to integrate multiple sources of information and display it in an easy-to-interpret, comprehensive, and practical manner, to enable clear communication across various divisions within mines. The dashboard, a user-guideline document, and supporting videos are available on the Mandela Mining Precinct website.

In addition, dissemination to industry has been through various seminars, conferences and presentations at industry forums. For example, the Mining Indaba, WITS Mining Institute Annual Seminar, and SAIMM Conferences.

Recommendations for application of the ESG Impact Lens Dashboard include:

- Users should familiarise themselves with the embedding and usage guidelines of each of the tools.
- Create a Google Firebase account to ensure integration across SATCAP tools.
- Maintain database integrity by inputting the correct and accurate data into data capturing worksheets.
- Seek expert advice on how to read and understand each indicator.
- Obtain buy-in from leadership on the regular review and usage of the dashboard outputs.

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

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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 digitalisation 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 Paraszcak 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 <i>et al.</i> (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).

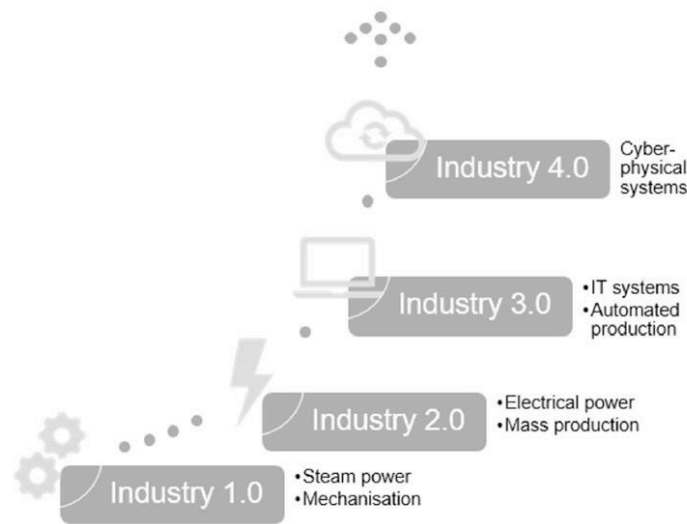


Figure 1. A depiction of the paradigm transformation in Industrial Revolutions.

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 (Löw *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.

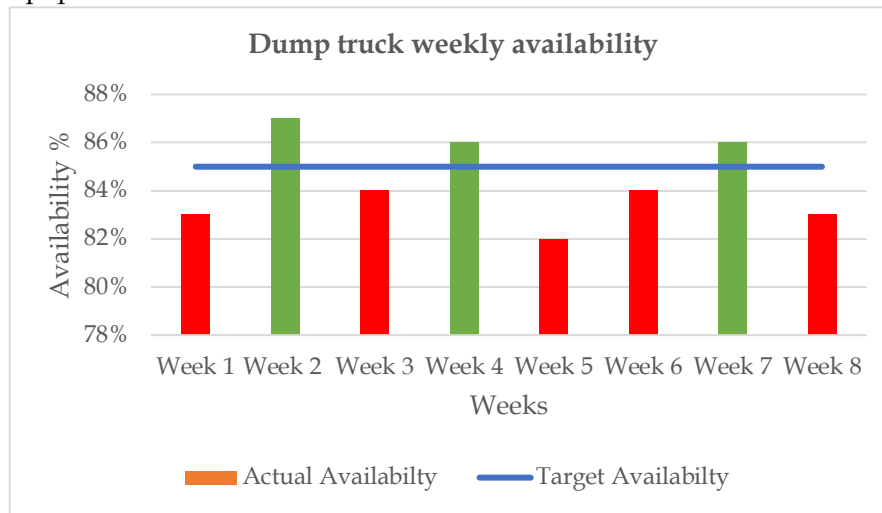


Figure 2. Machine availability results for eight weeks

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 **week 2 (4900 BCM)**, while the lowest was in **week 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.

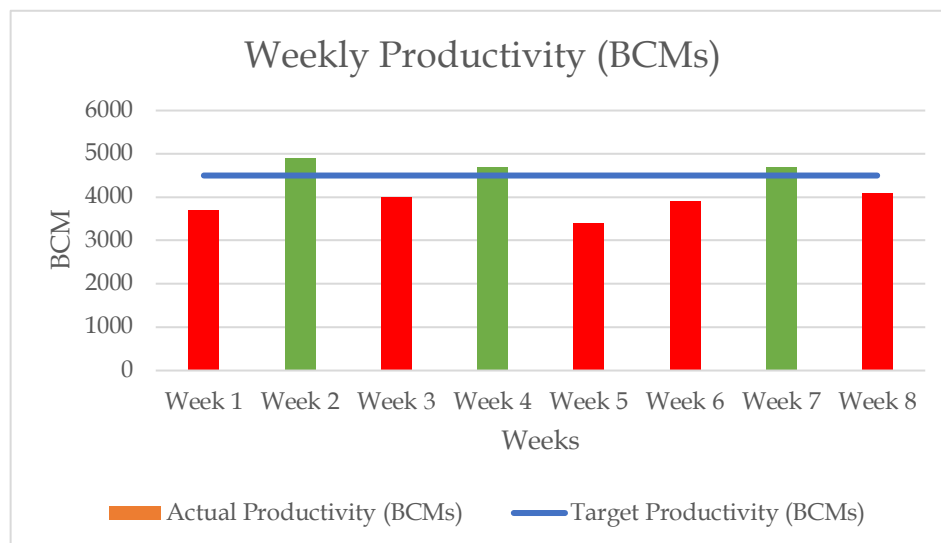


Figure 3. Weekly production results.

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.

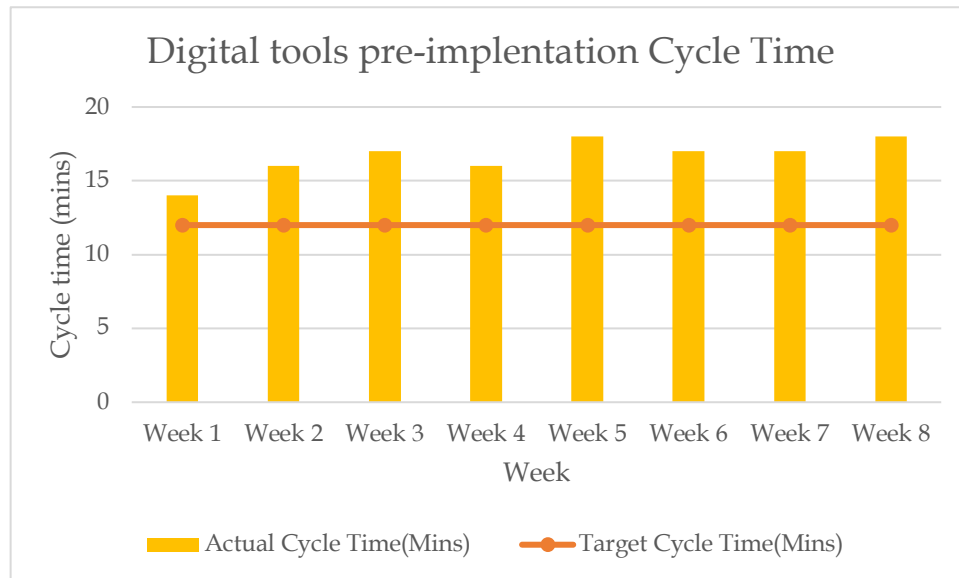


Figure 4. Cycle time analysis pre-implementation of automated dump trucks.

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.

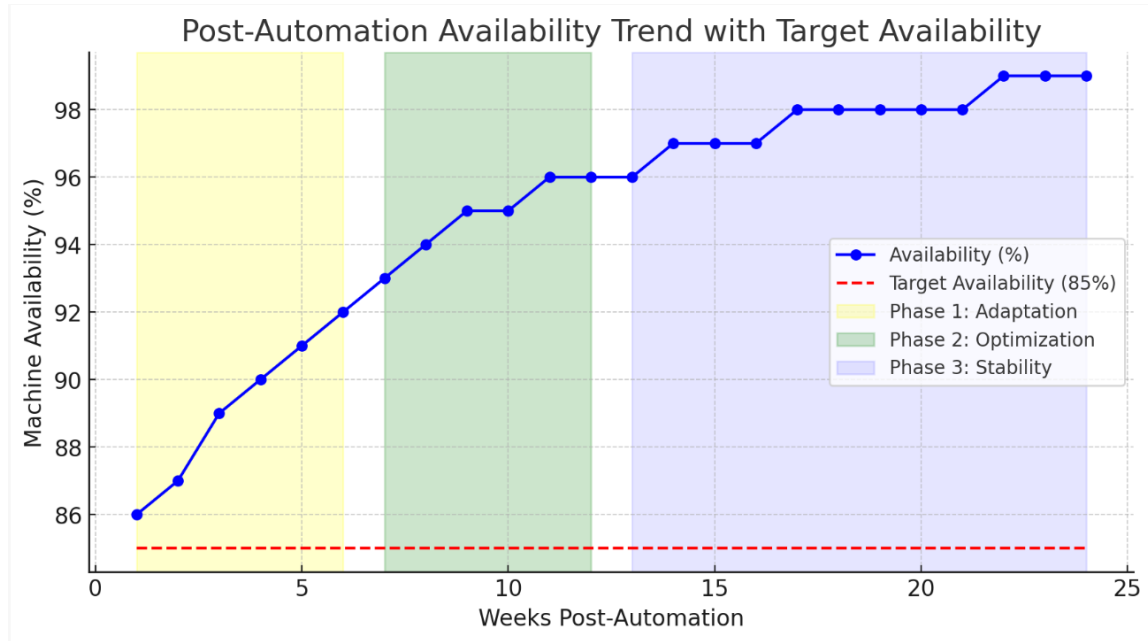


Figure 5. Availability trend analysis post-automation.

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 was 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.

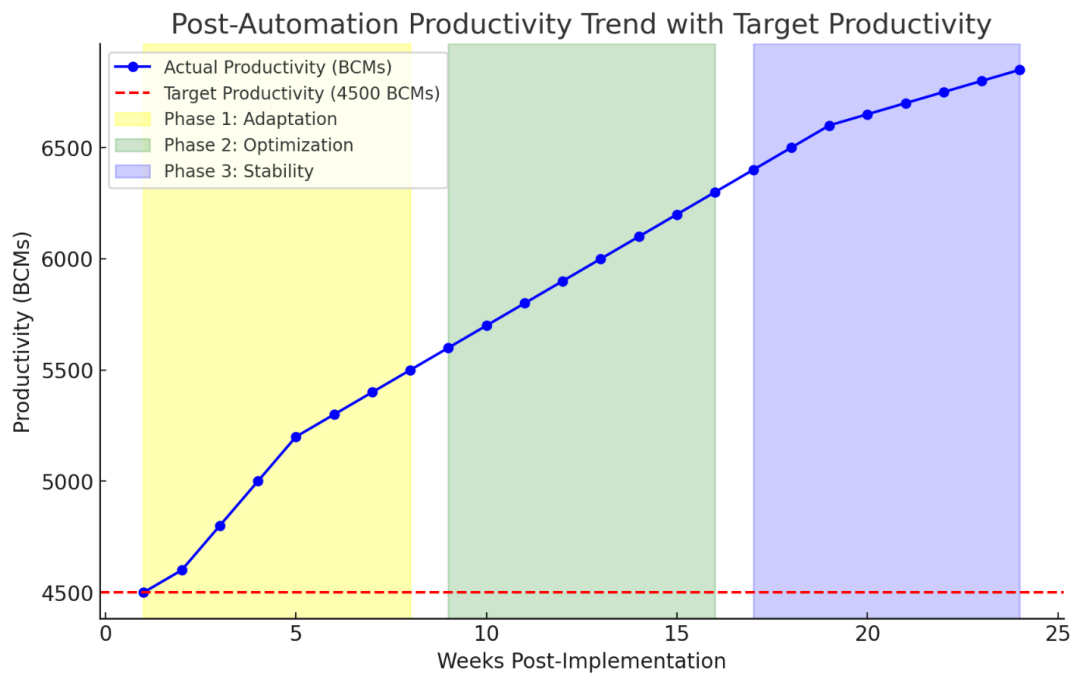


Figure 6. Post automation productivity trends.

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.

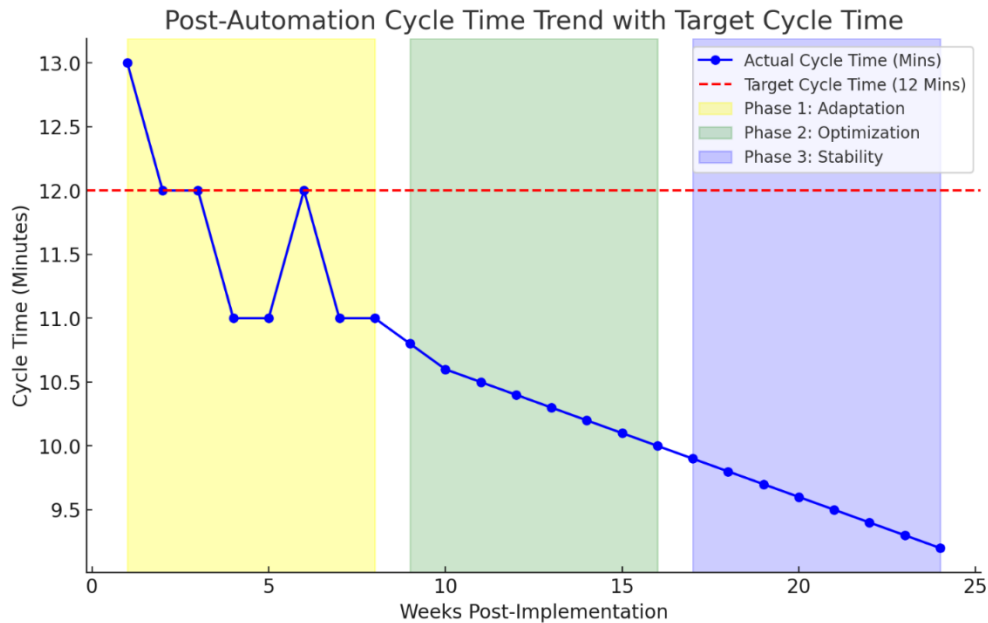


Figure 1. Post automation cycle time trend analysis.

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.

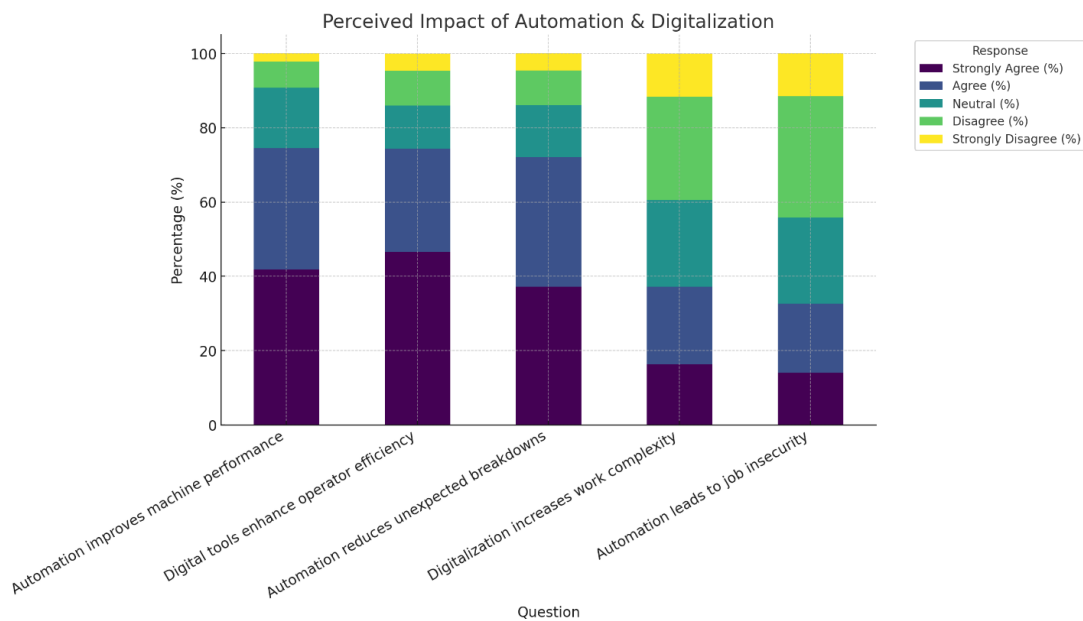


Figure 8. Distribution of responses on the perceived impact of automation by various personnel at the company.

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.

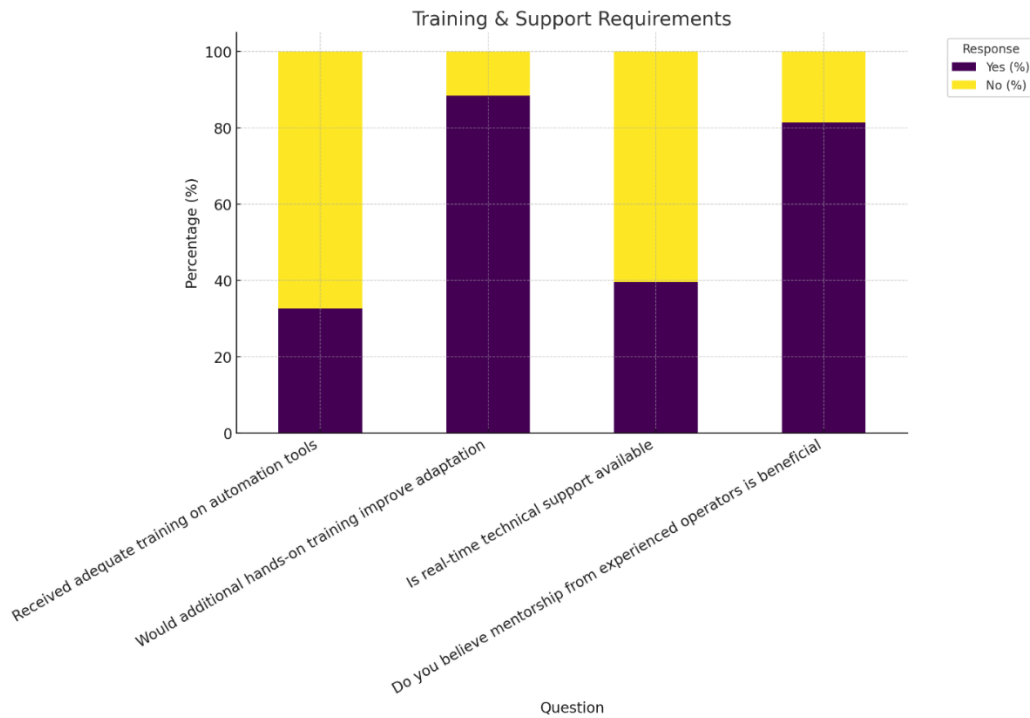


Figure 9. Training and support requirements results from the workers.

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.

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Utilisation of drone technology to monitor blasting performance for the undercutting of Lift 2 block cave at Palabora Mining Company

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Block cave mining relies heavily on accurate blasting to provide free ore movement and avoid the unintended creation of pillars. Palabora Mining Company (PMC) utilised the cavity monitoring system (CMS) to oversee blasting during undercutting. However, the CMS system not only offers limited accessibility and line of sight, but it also produces noisy data (data with errors) with reduced accuracy. This paper investigates the use of the Elios 3 drone to monitor blasting operations and assess alignment with planned designs at PMC, while also comparing it to CMS scans. The drone, outfitted with LiDAR sensors and high-resolution cameras, conducted a survey of a 4.8 m cavity across three flights lasting six minutes each. It successfully acquired comprehensive spatial data that was converted into high-resolution 3D models using FARO and Leica Geosystems software. The results revealed significant discrepancies between planned and actual blast designs. This included instances of overbreaking, underbreaking, and unintended pillar formation, which adversely affected ore flow and mine stability. The Elios 3 drone surpassed the CMS in data quality by securely traversing hazardous areas. Furthermore, it provided accurate data, hence offering useful insights for enhancing blast execution. The drone further minimised human exposure to hazardous conditions. These findings underline the potential of drone technology to optimise blasting operations, improve safety, and extend the operational lifespan of underground mines.

Keywords: drone, block caving, blasting, undercutting, monitoring, cavity monitoring system

INTRODUCTION

Block caving is a high-tonnage underground bulk mining method particularly suited for massive, low-grade ore bodies (Rashidinejad *et al.*, 2014). It is dependent on the controlled collapse of the orebody by its own weight to permit the movement of the broken rock through draw points to the production level (Morales *et al.*, 2024). This method is very efficient and economical and is recommended for stable and strong rock masses (Moss *et al.*, 2006). However, its success is grounded in good engineering and close monitoring to ensure that the cave develops and remains stable. Undercutting is a very important step in block caving. It involves blasting a horizontal slot at the base of the orebody to initiate the caving process (Kovalenko *et al.*, 2021).

The purpose of undercutting is to prepare the rock mass in such a way that gravity can pull and move the ore with ease. The height and design of undercut play a crucial role in controlling fragmentation, ore flow and mining operation efficiency (Morales *et al.*, 2024). Bad undercutting may cause ore hang-ups, irregular cave propagation, and pillars, which are unsafe and unproductive (Xia *et al.*, 2019). Accurate blasting operations during the undercutting stage of block mine caving are necessary.

This is crucial for avoiding excessive blasting, which can result in unintentional rock fractures, unnecessary displacement of materials, and, at times, instability. Excessive blasting might also lead to greater ore dilution, damage to infrastructure, and a rise in maintenance expenses.

Insufficient fragmentation will lead to challenges in centralising all ore during the clearing process (Morales *et al.*, 2024). Underbreaking, on the other hand, results in insufficient fragmentation, leaving unbroken ore behind (Kovalenko *et al.*, 2021). This can result in extra secondary blasting and reduced caving efficiency by causing delays in production and increasing operational expenses. In addition to over- and underbreaking, unintended pillar formation is another common issue in block caving. The presence of these pillars can obstruct ore flow and heighten stress levels (Moss *et al.*, 2006). This may ultimately lead to structural collapses or damage to machinery. Furthermore, the development of pillars may lead to a shortening of the lifespan of a mine.

Palabora Mining Company (PMC) uses the cavity monitoring system (CMS) to monitor the blasting area during undercutting. However, the CMS system not only offers limited accessibility and line of sight, but it also produces noisy data (data with errors) with reduced accuracy. Operational delays and safety risks are also common when using the system. Given these limitations, there is a need for an alternative monitoring approach that can provide higher accuracy, improved safety, and real-time insights into blast performance. While drone technology has gained traction in mining operations, its application in blasting performance monitoring for block cave mining remains underexplored.

It is in this light that the use of the Elios 3 drone is explored to monitor blasting operations and assess alignment with planned designs at PMC. The Elios 3 drone is specifically designed for confined and GPS-denied environments. It is equipped with LiDAR sensors and high-resolution cameras capable of capturing detailed three-dimensional spatial data. Therefore, the aim of this paper is to assess the effectiveness of drone technology in monitoring blasting performance during the undercutting of Lift 2 block cave at PMC.

METHODOLOGY

Study Area and its Geological Setting

This research was conducted at Palabora mine, Limpopo Province, South Africa, near the town of Phalaborwa. The mine is ranked as one of the largest copper deposits found in carbonatite worldwide. The mine has been operating since 1965 (Bezuidenhout, 2018). Palabora mine forms part of the Palabora Igneous Complex, an intrusion of carbonatite that was formed around 2060 million years ago. Within this deposit are found three main rock types, namely phoscorite, carbonatite, and banded carbonatite, all of which contain economic copper (Cu), magnetite (Fe), and rare earth elements (Gómez-Arias *et al.*, 2022).

The chalcocite group of minerals, chalcopyrite, and bornite occur in silico carbonatite and banded carbonatite as the major copper minerals. There are important faults like the Southwest Fault Zone (SWFZ) and the Mica Fault, which is particularly associated with cave propagation and ore recovery at Palabora mine (Ngidi & Pretorius, 2010). The history of mining in Palabora is such that it started as an open-cast mine which reached its ultimate depth at 800 m before it transformed into an underground block cave in 2002 (Brummer *et al.*, 2004). This underground operation utilises a block caving method that capitalises on gravity for breaking and moving ore at low drill and blast costs. Draw points are used for ore extraction underground, then it gets crushed and finally transported using conveyor belts for processing on the surface.

Presently, the mine produces 30,000 to 33,000 tonnes of copper ore daily for on-site processing (Sainsbury *et al.*, 2016). The first block cave was named Lift 1, and it was situated beneath the crown of the open pit at a depth of 1200 m. Although caving commenced in 2004, changing from open pit to underground led to North Wall failure in the same year. This was a major slope failure triggered by the progression of the cave beyond its intended boundary. Due to the slope failure, the east side required some modifications on draw point controls, as the failure led to poor fragmentation (Richard & Sulemana, 2015; Ngidi & Pretorius, 2010). Ore flow posed major challenges because of its blocky nature

within banded carbonatite (Ngidi & Pretorius, 2010). Be that as it may, Lift 1 ran efficiently for almost 20 years, demonstrating that block caving could be used on strong competent rocks (Sainsbury *et al.*, 2016). Lift 1 resources are almost depleted; however, in 2018, the development of Lift 2 was started to extend the mine's depth to 1400 m and increase its lifespan (Figure 1) (Robert Atkins Andre, 2014). Advanced monitoring techniques were introduced to prevent sinkholes and pillar collapses. The mine operates under high-stress conditions, requiring numerical analysis and earthquake monitoring. It has been noted that the development of caves in Lift 2 is much more progressive in relation to the SWFZ than the other areas and therefore poses a greater threat to surface structures (D. Sainsbury & B-A Sainsbury, 2016).

Controlled draw plans and enhanced blasting techniques were introduced for stress coping and continuous production. Palabora mine has gained international fame due to several factors, among them being its deep block caving system, complex geology and large scale of activities. Moving from open-pit to underground mining phase and continuation of construction work at Lift 2 require application of state-of-the-art surveillance technologies, including drones aimed at improving ore recovery and durability of surrounding rock mass.

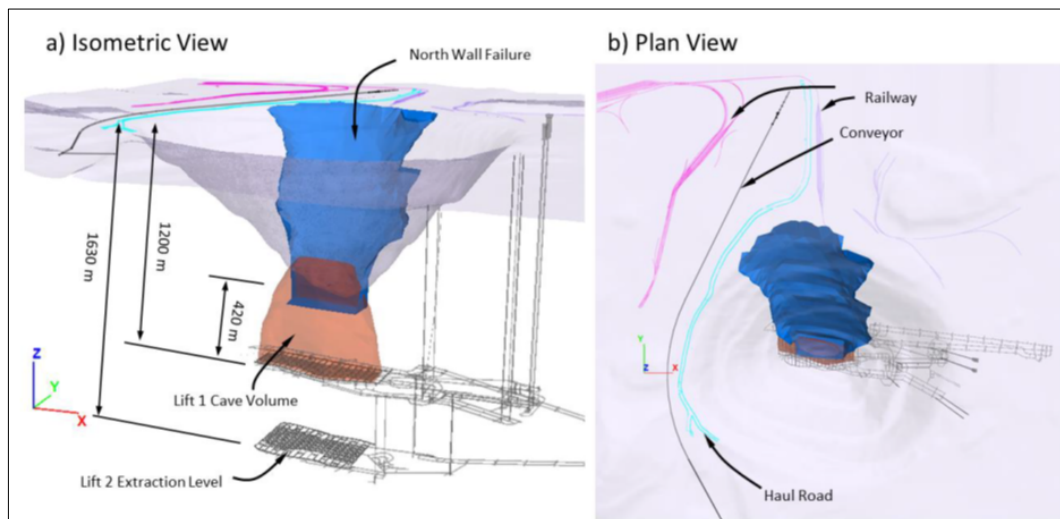


Figure 1. Isometric view and plan view of the Palabora mine, pit, Lift 1 and Lift 2 (D. Sainsbury & B-A Sainsbury, 2016).

Description of the Elios 3 Drone

Elios 3 is a specialised indoor drone meant for inspection and mapping in areas where there is no GPS signal or which are too confined for GPS monitoring to work. This indoor drone is created by Flyability with features that include a protective structure which is able to withstand collisions, hence suitable for flying safely in underground mines. By using LiDAR-stabilisation-based simultaneous localisation and mapping as well as visual-inertial odometry cameras, the drone can be operated with accuracy even without reference from the GPS. This ensures real-time mapping and accurate positioning in complex environments. To ensure that it remains reliable in dangerous environments, the drone has a feature that makes it automatically return on getting a signal. The presence of advanced cameras and sensors means that this model can offer both detailed visual and 3D analysis. For the best images, it is designed with a 4000 pixels (4K) camera with a pod that can be tilted up to 180°. Furthermore, the forward looking infrared thermal camera is used for detecting hot spots or leakages. It includes a light detection and ranging (LiDAR) system that produces point clouds geo-referenced data; serving as an efficient solution for geotechnical investigations and underground mapping. Depending on the weight, it can hover in the air for between 9 and 12.5 minutes. The standard model is splash- and dust-protected (Ingress Protection 44 (IP44)), but the LiDAR payload has an IP68 rating, which means that it can be used in tough environments.

Description of the Geosight NX-150 CMS Scanner

The Geosight NX-150 CMS scanner is tough laser scanning equipment made specifically for underground mines. This scanner utilises time-of-flight technology that helps in gathering high-precision 3D spatial data. It provides detailed scans for tunnel profiling, stope monitoring, and structural assessments with a 310° x 360° field of view and at an angular resolution of 0.1°. The scanner is connected either by wireless using WiFi or through cable, therefore easily used in various places such as mines and industries. For maximum protection against dust and water, the NX-150 has been fitted with a military-grade aluminium body and an IP65 protection rating. It can work under extreme temperatures ranging from -30°C to +60°C, thus is suitable for various underground conditions. In addition, it has a 21-volt rechargeable battery that has a long-life usage. It is compatible with laptops or tablets for data transfer and processing. It also enhances on-site calibration and provides loaner units while being repaired to ensure little or no interruption during emergency operations.

Data Collection using the Elios 3 Drone

To gather LiDAR point cloud data, the Elios 3 drone was flown into the undercut after blasting. The undercut was about 4.8 m across. Before the drone could be flown, three reference discs were placed strategically in three different areas in the undercut. These discs acted as a reference point for the drone. In the absence of any references, the total station was used to take measurements of the position of the discs or the survey prisms so that the point clouds could be georeferenced properly to the mine plan. After placing the discs or scanning the prism, calibration of the drone's LiDAR system and analysis of risks were done just before it was flown. For proper coverage of post-blast areas, the drone had to fly three times for six minutes each. The Elios 3 used LiDAR technology alongside high-resolution cameras to take images of the surrounding area. It also collected thermal as well as visual pictures for further analysis during each flight. High-resolution 3D point clouds representing the exploded regions were produced by the LiDAR sensors mapping the cavity.

Data Collection using the Geosight NX-150 CMS Scanner

A total station was used to establish control points and prisms for geo-referencing in the undercut. The undercut height was 4.8 m. Before scanning, the Geosight NX-150 CMS scanner and accessories (boom system, buggy, manual mount) were checked for correct operation. The scanner was mounted on a boom, allowing scanning inside the cavity while keeping the operator 15 m away. The scanner was connected by cable and WiFi to a tablet for real-time data transfer and live viewing. Scanning was initiated remotely. The LiDAR performed a full 360° sweep, generating a dense 3D point cloud of the blasted cavity. Multiple scans were taken from different positions to minimise blind spots. Live monitoring confirmed coverage. If gaps were identified, the scanner was repositioned to capture them. Each CMS scan setup, including positioning and data capture, took about 40 minutes. After scanning, the data was geo-referenced using total station control points. The point cloud was then used for volumetric analysis and to track blast performance.

Data Processing and Analysis

Flyability Inspector 5 was used to start processing and geo-referencing Elios 3 drone LiDAR data. It begins by importing the raw LiDAR point cloud (LAS, PLY, or E57) and visual images into Inspector 5. The two types of files are aligned automatically in the Inspector 5 to create one coherent 3D point cloud. It also filters out any irrelevant data, such as those arising from either dust or reflections, before segmenting the point cloud. This is to allow for easier visualisation of important features within the mine, such as pillars and draw points, as well as voids, among others. On the other hand, GeoSight scan manager is employed for analysing raw scans of NX-150 CMS LiDAR data. The imported point cloud was cleaned by eliminating noise, reflections and distortions for better visibility. It helps in segmenting out all the features, such as the stopes, draw points, and voids. This is achieved through aligning several scans to come up with one overall underground openings 3D model.

Geo-referencing, Alignment, and Quality Control

The point cloud from the drone and CMS, after being pre-processed, was exported out for geo-referencing as well as refining the accuracy. Faro Connect was then used for point cloud registration and geo-referencing. Control points from either total station markers or surveyed reference discs help in properly doing this. This step also included coordinate transformations between UTM or mine grid

systems so that all scans match the block cave mine plans with respect to relative space around them. The last step before exporting georeferenced point clouds involves quality control procedures aimed at eliminating alignment errors and reducing deviations as much as possible. The point clouds undergo further analysis in Leica Cyclone 3DR upon completion of this phase. In the same software package, the point cloud is refined and matches with the mine's coordinate system. A visual comparison is made between the scan geometry and the undercut layout to identify any anomalies. The anomalies include pillars, over- and under- breaking. Colour coding is done to show different levels of progress in drawing point excavation.

RESULTS AND DISCUSSION

To monitor the effectiveness of blasting performance in Lift 2 of Palabora block cave, the Elios 3 drone was deployed. The data indicated significant inconsistencies with the intended blast design, such as overbreaking, underbreaking, and the creation of extra pillars. It was possible to identify and describe the differences seen in the drone scans of the planned and actual blast results so as to make any necessary changes in succeeding blasting operations from this information. These figures highlight some of the differences between the actual execution and the intended blueprint of the blast taken from the drone survey.

Observations on Excessive Blasting

Figure 2 shows examples of severe overbreak observed during blasting. Figures 2a and 2b compare the planned blast perimeters with the actual outcomes. Red areas mark regions where the blast exceeded the design boundary (overbreak), while blue areas indicate underbreak—material left intact. Figure 2a reveals a serious case of overbreak: 95.6% of measurements exceeded the intended perimeter, with a maximum depth of +8.3 m. Poor blast control and likely excessive local charge concentrations are evident. In Figure 2b, 69.8% of measurements show overbreak, reaching a maximum of +3.3 m. Here, the pattern points to more localised overcharging, seen in concentrated red zones. Overbreak of this scale has major operational consequences. Large, unplanned voids can accelerate cave propagation and undermine rock mass stability. They also increase the demand for secondary ground support, raising both cost and risk. Comparing the planned and actual blast profiles helps pinpoint performance issues and guide corrective action. Consistent, precise blast design and close monitoring are critical to improving control and reducing unplanned overbreak.

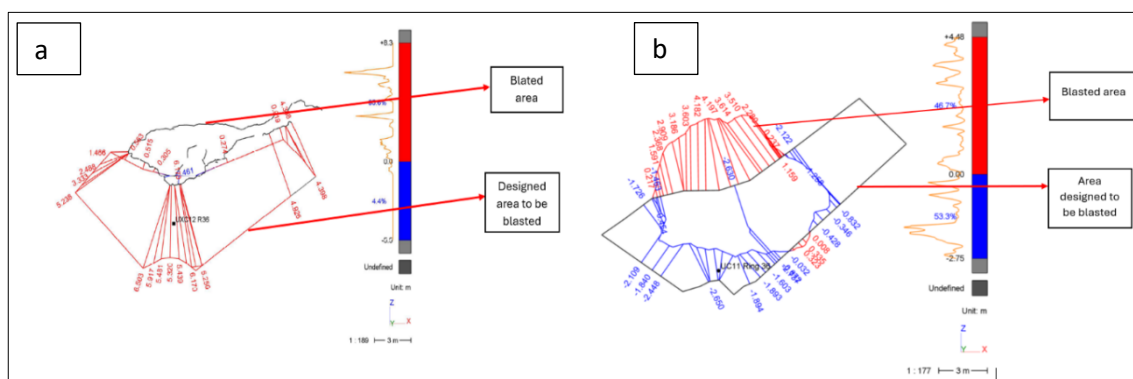


Figure 2. 2D sectional views of over-breaking from drone scans (a, b).

Under Breaking Effects

Figure 3 (a,b) compares the drone scan images for planned (blue) and actual (gold) blast areas; it highlights the level of underbreaking for this case. Figure 3a identifies areas at the bottom where there is a clear underbreak, as seen by large intact sections. On the other hand, the upper part has managed to experience some form of material breakage with little effect on the lower part. Figure 3b also proves that there was underblasting in some of the areas. It is clear that underbreaking occurred between points R39 and R43. This indicated that the applied energy was inadequate to break the rock mass (Yang *et al.*,

2024). However, failure of blast design to consider changes in rock strength, inclusive of if there was under-optimisation in hole spacing, burden, or charge distribution, could make the design a secondary issue also. Even though there is effective breaking at some points, most of the rock parts are non-fragmented. This may cause blockages in orebody propagation. Therefore, there will be challenges in recovering ore and the possibility of creating strong non-caving pillars.

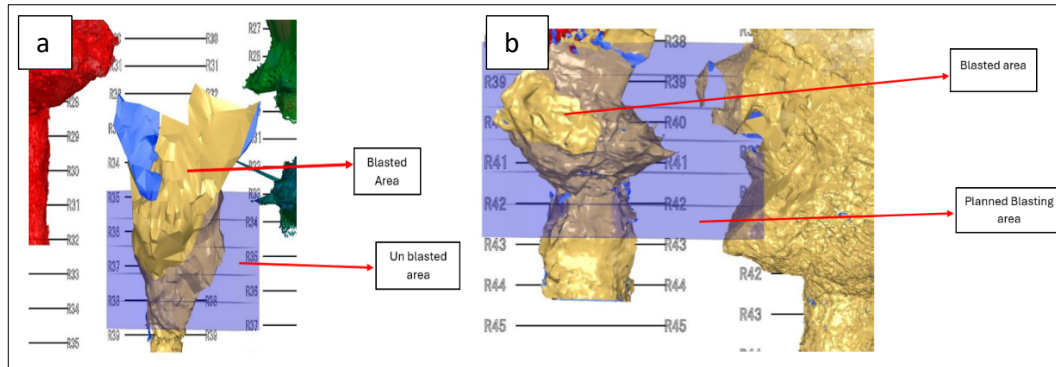


Figure 3. Comparison of blasted areas vs planned blasting zones and ring design from a drone scan (a, b).

Pillar Formation

Unblasted rock masses create pillars that prevent a continuous caving phase. Figure 4 indicates many areas where pillars are forming. A lack of sufficient blast energy or the blast design has led to unbroken rock and the presence of multiple evenly spaced pillars. The pillars can be identified near rings R31, R32, and R35 in Figure 4. A large pillar can also be observed on the right side of the figure under UCX11. Ore recovery, surrounding rock strength and overall cave formation efficiency may be affected by unintended pillars. Broken ore which may be unable to move freely in its natural path due to these pillars results in draw point blockages. In addition to this, they lead to uneven distribution of stress, thereby increasing chances of local collapse or seismic activities (Linzer *et al.*, 2021). Solid pillars also disturb the formation of caves, making it necessary to use more explosives during blasting (Gams, 2023); thereby incurring higher annual expenses with subsequent time overruns.

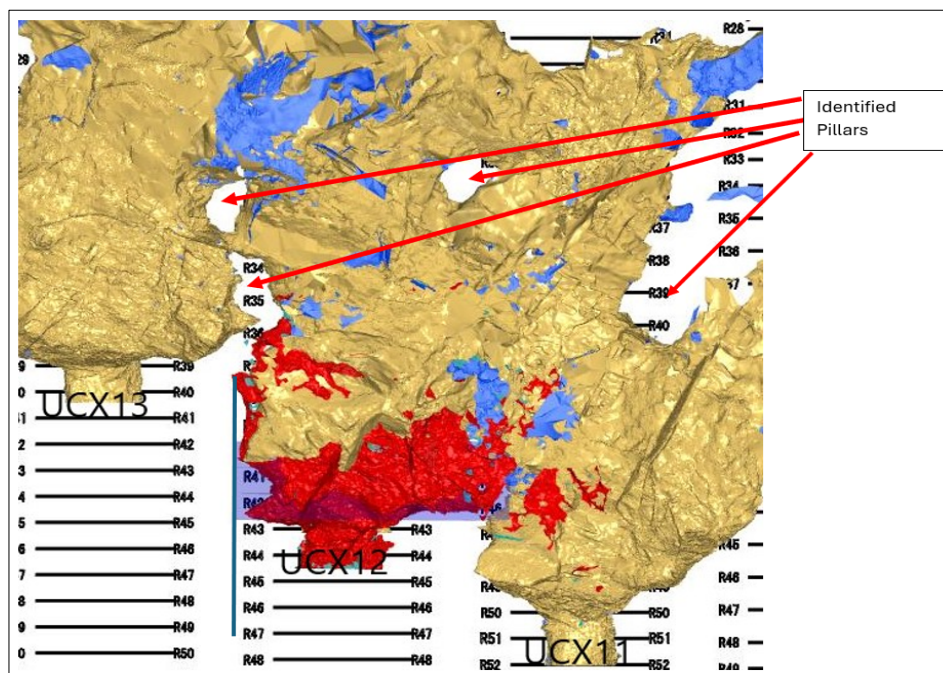


Figure 4. Identified pillars and unbroken rock from the drone scan.

Comparison between Elios 3 Drone and Traditional CMS Monitoring

In Figure 5(a), the lower red scan shows the drone-derived point cloud. The upper green scan represents the CMS data. Both are superimposed on the planned undercut geometry to enable spatial comparison of coverage and depth penetration. Figure 5(b) isolates the drone scan and overlays it with the undercut and ring designs. The scan shows strong alignment with the planned geometry in both volumetric extent and shape fidelity. Figures 5(c) and 5(d) compare CMS scans to the ring and undercut designs respectively, illustrating the CMS's more limited volumetric coverage and more fragmented representation of the blasted volume. The drone data is denser and more continuous, particularly in capturing complex blasted voids. CMS scans cover a narrower zone, limiting interpretability in some areas. This distinction is critical when evaluating the accuracy and completeness of post-blast volumetric models.

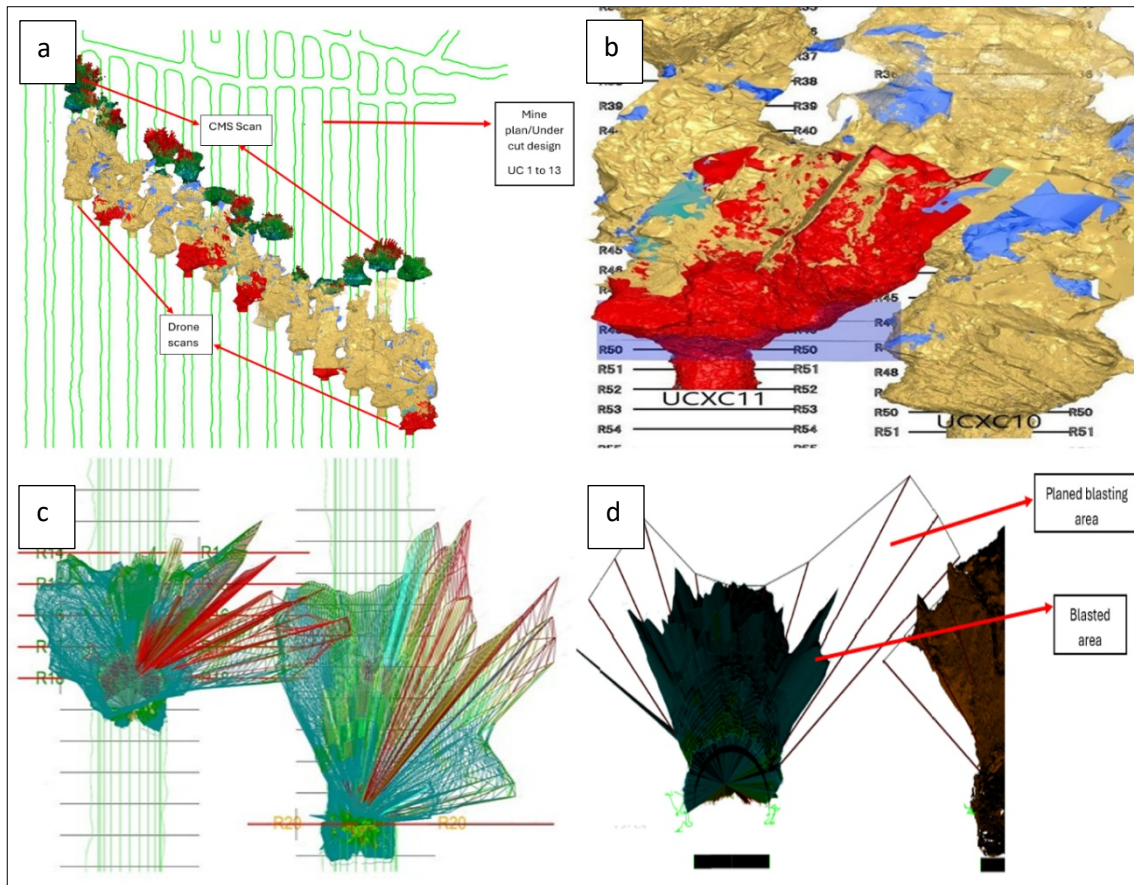


Figure 5. Comparison of CMS and drone-based scanning results against undercut and ring design plans. (a) Combined visualisation of mesh models generated from drone and CMS scans, overlaid on the planned undercut geometry; (b) Visualisation of drone-derived mesh compared to the planned undercut and ring designs; (c) and (d) Visualisation of CMS scan meshes compared to the planned undercut and ring designs. Different mesh colours are used for visual distinction only and do not represent material type or data source.

Comparison between Elios 3 Drone and Traditional CMS Monitoring in terms of Safety

Safety is one area where the Elios 3 drone offers clear operational gains over CMS scanning in the Lift II block cave undercut. CMS scanning requires the operator to work within 15 m of the cavity. Each scan takes about 40 minutes, during which the operator remains exposed to geotechnical hazards. It also requires drawpoints to be cleared to at least 50% post-blast to allow scanner access, delaying scanning and increasing downtime. The static position of the CMS causes shadowing in the scan data. The drone removes these constraints. It is flown remotely, with the operator positioned 15 to 50 m away, outside the hazard zone. Drawpoints do not need to be cleared before scanning. A typical flight takes six

minutes, with scanning and data capture finished in under 15. Operator exposure is reduced by an estimated 70–80%, based on both time and distance. The drone's mobility also reduces shadowing, producing more complete point clouds. Drone operation requires basic pilot training and knowledge of site safety protocols. CMS scanning demands more specialised training to safely position and operate the equipment in confined, hazardous areas. The lower risk exposure and simpler training requirements make drone-based scanning well suited for frequent blast monitoring in block cave operations.

CONCLUSION

This study assessed the use of the Elios 3 drone for monitoring blast effects during undercutting of the Lift II block cave at Palabora mine, with a direct comparison to conventional CMS scanning. The aim was to evaluate the effectiveness of drone-based scanning in capturing post-blast cavity geometry, identifying deviations from design, and supporting blast performance assessment. The Elios 3 drone produced high-resolution 3D mesh data that allowed for detailed evaluation of overbreak, underbreak, and pillar formation. The results showed that overbreak reached up to +8.3 m in some areas, increasing the risk of cave instability and contributing to potential dilution. Underbreak was also observed, particularly between levels R39 and R43, where insufficient blast energy left intact rock in the drawpoint zone. This resulted in the formation of unintended pillars, clearly visible in Figure 4, particularly near R31, R32, R35, and beneath UCX11. Such pillars obstruct ore flow, increase the likelihood of drawpoint hang-ups, and raise operational risks due to stress redistribution and potential seismic activity. The Elios 3 drone provided superior scan coverage compared to CMS, reducing shadowing and allowing full mapping of complex cavity geometry. Importantly, drone-based scanning required no drawpoint cleaning and reduced operator exposure time and distance, improving both safety and operational efficiency. CMS scanning was slower, required extensive setup and cleaning, and produced more limited data. Accurate monitoring of blasting outcomes is essential for optimising cave performance and managing operational risk. Based on the findings of this study, the Elios 3 drone is recommended for routine blast performance monitoring at Palabora mine. Its advantages in data coverage, scanning efficiency, and operational safety make it a preferable tool for this application compared to conventional CMS scanning.

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Tebello Lepheana

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I'm Tebello Lepheana, a Mine Surveyor based in Evander, Mpumalanga, with over 15 years of experience in both underground and open-pit mining. My career has been built on a mix of hands-on surveying, leadership in survey operations, and adopting new technologies like 3D laser scanning and drone-based underground mapping. I've always believed that accurate, efficient survey work is the foundation of safe and productive mining, and I've made that my focus throughout my career. I started off as a Learner Surveyor at Concor Mining, where I got my first real taste of the mining environment. From there, I joined Evander Gold Mines, where I worked for a full decade. That's where I really cut my teeth—leading underground surveys, setting out mining layouts, and making sure that every line, peg, and measurement helped the mine run smoothly. When the mine eventually closed, I knew I had to grow further. Over the years, I've taken on roles that pushed me to grow technically and personally. At Leviking Technical Services, I managed pit surveys and drill designs. Later, I moved into a Mine Surveyor role in the DRC with Alphamin Bisie Mine, handling underground survey work before COVID brought things to a halt. That break didn't slow me down for long. I joined Dwyka Mining Services and worked on some exciting projects using 3D scanning, point cloud modelling, and the Blast Gyro system. I loved working with new tech seeing how data could shape smarter mining and I supported projects all over Africa. Right now, I'm working as a Supervisor Survey (Underground) at Palabora Mining Company. I lead a strong team, oversee underground drone scanning, manage survey data processing, and ensure our work meets safety and compliance standards. Training and mentoring junior surveyors is a big part of what I do, and I take pride in helping others grow. I've earned a National Diploma in Mine Surveying from UNISA, and I also hold several certifications from the Chamber of Mines. I'm a registered member of the South African Geomatics Council, and fluent in multiple South African languages, which has always helped me work across different teams and regions. If there's one thing that defines my approach, it's the belief that technology and experience should work hand in hand. Whether it's using drones for underground scans or turning raw data into actionable insights with tools like MicroStation and Cyclone 3DR, I'm always looking for ways to improve and modernize the way survey work is done. Looking ahead, I want to keep pushing boundaries taking on more leadership, more innovation, and ultimately contributing to mining operations that are not only productive but safer and smarter too.

Grinding circuit throughput optimisation through first-principles digital twin modelling

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The global mining industry is increasingly leveraging digital technologies to address persistent challenges in productivity, resource efficiency, and process stability. Grinding circuits, as energy-intensive and highly variable systems, represent a key opportunity for optimisation through real-time, holistic model-based decision support. Traditional operation methods, which are characterised by manual monitoring, and unit-based control strategies, often result in suboptimal throughput and inconsistent product quality. In response, a digital optimisation framework was developed for a gold processing plant in West Africa. The grinding circuit included a SAG mill, ball mill, trommel, pump boxes, and hydrocyclones. A hybrid digital twin framework, combining first-principles and empirical models, was calibrated using operational survey data collected in early 2024. The model was used to maximise hydrocyclone overflow throughput while satisfying process constraints such as particle size, power draw, and hydrocyclone pressure. Three optimisation scenarios are explored, identifying optimal control setpoints yielded 3% throughput gain; suggesting distinct configuration parameters achieved 7.6%; incorporating an additional hydrocyclone reached 15% improvement over the baseline. This paper validates the use of calibrated physics-based digital twins for realising substantial, verifiable performance enhancements in complex industrial comminution circuits.

Keywords: digital twin, grinding circuit optimisation, energy efficiency, first-principles modelling

INTRODUCTION

Digital transformation is progressively reshaping the mining industry, integrating advanced analytics, automation, and interconnected systems into mineral processing operations. Grinding circuits, encompassing equipment such as semi-autogenous grinding (SAG) mills, ball mills, and classification systems (hydrocyclones, screens), are a primary focus for these digitalisation efforts (Bascur & Soudek 2019; Young & Rogers 2019). As frequently the operational bottleneck of concentrators, the performance of the grinding circuit dictates overall plant throughput and significantly influences downstream recovery efficiency (Wills & Finch 2016). Even marginal improvements in mill throughput can yield substantial gains in productivity and profitability, making optimisation a critical objective (Giblett & Putland 2018). In a landscape marked by volatile commodity prices and stringent operational cost management, maximising the tons of ore processed per hour is critical to maintain competitiveness.

The energy consumption associated with comminution (crushing and grinding) further underscores the importance of optimisation. Grinding circuits are notoriously energy-intensive (Napier-Munn 2015), accounting for potentially 2–3% of global electricity consumption and often consuming up to 50% of a mine site's total energy budget (Allen Marc 2021). Consequently, enhancing grinding efficiency and throughput directly translates to reduced energy expenditure and lower unit operating costs.

Achieving even a small improvement in throughput or energy efficiency can lead to significant financial and resource conservation benefits.

Sustainability imperatives also drive the need for optimised grinding operations. Reducing the specific energy consumption (kWh per ton of ore processed) yields direct economical, and environmental benefits (Bouchard, Desbiens & Poulin 2017a). Digital optimisation tools enable mines to continuously adjust operating parameters to maintain peak performance, potentially reducing energy usage by 5–15% without asset modification (W.A. Gough 2015; Bouchard *et al.*, 2017a). This involves utilising existing processes more effectively, enhancing both energy efficiency and throughput concurrently. Furthermore, stable and efficient grinding circuit operation can minimise waste generation, improve downstream metallurgical recovery, and potentially extend the operational life of major equipment, contributing to more sustainable mining practices.

Grinding circuits present unique and significant operational challenges due to their inherent characteristics and their pivotal role in the overall mineral processing flowsheet. The primary goal, typically maximising throughput while achieving a target product size distribution (often characterised by d_{80} , the particle size at which 80% of material cumulatively passes) suitable for downstream separation processes (e.g., flotation, leaching), is complicated by several factors:

- *Process Complexity and Non-Linearity:* Comminution involves intricate physical phenomena like particle fracture, material transport within mills, and classification in hydrocyclones or screens. These processes exhibit highly non-linear behaviour. For instance, mill power draw does not scale linearly with feed rate or mill speed, and hydrocyclone separation efficiency is a complex function of feed properties and operating pressure (Olivier & Aldrich 2021). The interactions between units are strong; changes in SAG mill operation directly impact the feed to the ball mill and hydrocyclones, creating coupled dynamics that are difficult to manage independently.
- *Variability:* Ore feed characteristics are rarely constant. Fluctuations in hardness, mineralogy, feed size distribution, and moisture content significantly affect grinding behaviour and energy requirements. Equipment conditions also vary due to wear. These variations act as continuous disturbances to the circuit (Sikström, Brown & Koorts 2022).
- *Time Delays:* Grinding circuits exhibit considerable transport and process lags. The response of the product size distribution to a change in feed rate or water addition may take tens of minutes to fully manifest, making real-time control tuning challenging (Yamashita *et al.*, 2023).
- *Measurement Limitations:* Key internal state variables, such as the precise particle size distribution within the mill, fill level, ore/ball charge or the circulating load composition, are often difficult or impossible to measure directly and continuously (Hodouin *et al.*, 2001). Operators rely on indirect measurements (e.g., mill acoustics and vibration monitoring, power draw, sump levels, density gauges) and infrequent laboratory samples, leading to incomplete process visibility.
- *High Energy Consumption and Grinding Efficiency:* Comminution is fundamentally energy-inefficient, with only a small fraction (~1–5%) of input energy creating new particle surfaces (Bouchard, Desbiens & Poulin 2017b). Inefficiencies arise from designs mismatched to current and drifting ore properties, high recirculating loads reprocessing already fine material, and operational deviations from optimal slurry density or mill load.
- *Throughput Maximisation Constraints:* Often, the SAG mill or the ball mill circuit limits overall tonnage. Relieving these bottlenecks might involve incremental upgrades like adding pebble crushing capacity, optimising classification, or improving feed preparation. However, each fix has limits, and pushing throughput can lead to trade-offs, such as increased wear rates, higher maintenance costs, or coarser product size potentially impacting downstream recovery. Determining the true economic optimum, balancing throughput gains against costs and recovery impacts, is complex due to these interacting constraints.

Traditional methods for tackling previous challenges have been through basic proportional-integral-derivative (PID) control loops for regulatory control, supplemented by manual oversight from experienced operators (Olivier & Aldrich 2021). However, the inherent complexity, non-linearity, significant time delays, and strong interdependencies within grinding circuits make purely manual or basic automated control suboptimal. Frequent variations in ore characteristics (e.g., hardness, mineralogy, feed particle size distribution (PSD)) and equipment condition continuously perturb the system, demanding constant adjustments that are difficult to optimise manually or with simple control logic (Ramasamy, Narayanan & Rao 2005). This often leads to conservative operation within a narrow ‘comfort zone’, sacrificing potential throughput and efficiency.

Advanced process control (APC) techniques, such as rule-based expert systems, fuzzy logic, and model predictive control (MPC), have been applied to grinding circuits with varying degrees of success. MPC leverages a dynamic process model to predict future behaviour and optimise multiple control actions simultaneously, while respecting constraints (Thivierge, Bouchard & Desbiens 2023). However, challenges remain, including the need for accurate and well-maintained process models, operator trust and acceptance, and the expertise required for implementation and tuning.

More recently, data-driven approaches using machine learning (ML) and artificial intelligence (AI) have emerged (Di Feo *et al.*, 2024). Techniques like decision trees have been used to extract operational rules from historical data (Olivier & Aldrich 2021). Reinforcement learning (RL) has shown promise in simulation studies, learning complex control policies to optimise profit-based objectives (Hallén *et al.*, 2019).

The proposed approach seeks to overcome the limitations of prior methods by utilising a first-principles based digital twin framework. This framework leverages fundamental engineering models of each unit operation, ensuring physical realism and adherence to mass and energy balances. Critically, these models are calibrated using plant-specific operational data, creating a hybrid approach that combines the predictive power of physics with site-specific empirical adjustments. The contribution of this work lies in demonstrating the development, calibration, and application of the proposed framework to an industrial gold processing circuit, showcasing significant performance improvements over an established baseline.

GRINDING CIRCUIT DIGITAL TWIN FRAMEWORK

The proposed framework provides a robust platform for simulating and optimising grinding circuit performance. It centres around a digital twin constructed from interconnected first-principles models of the individual unit operations, calibrated against plant data.

Overview

The digital twin serves as a high-fidelity virtual replica of the physical grinding circuit. It is designed to be modular, allowing individual unit models to be updated or replaced without affecting the overall structure. The core comminution model components simulate the physical processes occurring within each piece of equipment, while the digital twin framework manages the flow of material and information between these components. An optimisation layer sits atop the simulation, systematically adjusting decision variables to achieve a defined objective (e.g., maximise throughput), subject to process constraints.

The simulation proceeds sequentially following the comminution process flowsheet. The output streams (solid flow rate vector and water flow rate) from one unit model become the input streams for the next. For closed circuits, the recirculation estimators execute internal iterations, passing stream data between the relevant unit models until a steady-state mass balance is achieved. This ensures that the overall circuit simulation represents a converged state. The optimisation engine then orchestrates the main simulation modules with trial decision variable values. The simulation is executed (including loop solver iterations), calculates key performance indicators (KPIs) and constraint values, and returns the penalised objective function value to the optimiser, which suggests the next trial variables until an

optimal threshold is met. The framework may interact with plant data sources like the distributed control system (DCS) or historians for calibration and potentially for online updates.

It is important to distinguish the timescale of the digital twin's calculated optimal setpoints from the underlying process control layers. While low-level PID controllers adjust actuators rapidly, often on a seconds timescale, the supervisory setpoints targeted by the optimisation (e.g., optimal mill feed rate, target slurry density, mill speed setpoint) are typically adjusted much less frequently. Due to the inherent process dynamics and response times of large grinding equipment, meaningful changes to these supervisory setpoints usually aim at steady-state optimisation and occur on the order of minutes, whether adjusted manually by operators or by higher-level control systems. The computational time required for the digital twin optimisation scenarios in this study aligns well with this minute-scale cadence. This confirms the framework's suitability for providing timely decision support in an offline advisory capacity or potentially serving as the calculation engine for an online supervisory control layer that updates targets for the plant's DCS at operationally relevant intervals.

Core Framework Components

The digital twin framework is built upon several interconnected components designed to simulate the grinding circuit and identify optimal operating conditions. The core components include:

Comminution Simulation Engine: The core of the framework, comprised of steady-state simulation models that mathematically describe the steady-state physical transformations (size reduction, separation) occurring within each unit. The modular engine is comprised of the following models; for a detailed breakdown of all model input, outputs and calibration parameters please refer to the Appendix A:

- **Unit Operation Models:**
 - *SAG Mill model (SAGM):* Simulates ore breakage, internal transport, and grate discharge using population balance concepts. Key inputs include mill speed (ϕ), ball charge (JB), and feed PSD (d_i). Outputs include product PSD (P_{pi}), power draw (W), and internal charge volume (J). The formulation integrates breakage kinetics and discharge mechanisms akin to those defined by Hinde & Kalala (2009).
 - *Ball Mill model (BLM):* Utilises similar comminution principles for finer grinding, predicting product PSD (P_{pi}) and power draw (W) based on speed (ϕ), ball charge (JB), and feed (F_{fi}).
 - *Crusher model (CRM):* Models size reduction of coarse particles based on closed-side setting (Css). It uses classification and breakage functions derived from principles established in models like Whiten (1972).
 - *Hydrocyclone model (HCM):* Simulates particle classification based on cyclone geometry (D_c, D_o, D_u , etc.), operating pressure (P), and feed slurry properties. It employs the widely adopted semi-empirical framework developed by Flintoff, Plitt & Turak (1987).
 - *Screen (SCM) & Trommel (TRM) model:* simulates size separation based on aperture h, wire d, angle theta, geometry. Efficiency calculations are primarily adapted from the Karra (1979) screening model.
 - *Pump Box models:* Modelled implicitly through mass and water balance calculations at stream mixing points, summing incoming flows and incorporating direct water addition (W_a).
- **Recirculation Estimators (SAGExM, HCExM):** Essential modules within the simulation engine that handle closed-circuit mass balancing. They iteratively pass stream data (solids flow vectors, water flows) between interconnected unit models (e.g., SAG-

Crusher-Screen loop, Ball Mill-Hydrocyclone loop) until the recirculating flows converge to a steady state.

- **KPI Estimators:** Calculate KPIs like particle size d80 and solids fraction (X_p) from the simulated stream data.
- **Optimisation Engine:** Leverages Bayesian Optimisation (BO) to systematically drive the simulation engine. It proposes trial values for decision variables, receives the resulting objective function value (hydro cyclone throughput), and intelligently selects subsequent trials to find the optimum.
- **Data Interface:** Connectors for managing ore feed characteristics (d_i , F_i), operational parameters, decision variable bounds, constraint bounds, and model parameters. Moreover, manages the integration of the identified optimal control setpoints with its proper destination.

While the unit operation models are grounded in first principles, they incorporate numerous parameters (e.g., breakage rate coefficients; classification parameters; power coefficients) that are determined through calibration against plant-specific operational data. This calibration step embeds site-specific empirical behaviour, making the overall digital twin a hybrid model, combining the predictive power and extrapolation capability of physics-based models with the accuracy derived from real-world plant performance.

Simulation Model Calibration

Calibration is a critical step to ensure the digital twin accurately reflects the actual plant behaviour. The methodology involved:

1. **Data Collection:** Gathering comprehensive operational survey data from the target processing plant. This includes feed characterisation, stream samples for PSD analysis throughout the circuit, flow rate measurements, density measurements (to calculate solids fraction X_p), mill power draws ($\dot{W}$), hydrocyclone pressures (P), and estimates of mill charge levels (J , J_B).
2. **Parameter Estimation:** Adjusting tunable parameters within the first-principles models (e.g., breakage rate parameters S_{1E} , K_1 , K_2 ; classification parameters α , β , F_1 - F_4 ; power model coefficients) to minimise the discrepancy between model predictions and the measured survey data. This is typically an optimisation problem itself, often solved using least-squares or similar fitting techniques.
3. **Validation:** Comparing the predictions of the calibrated model against the survey data points for key KPIs:
 - Mass flow rates of solids and water in major streams.
 - PSDs of key streams (e.g., mill discharge, cyclone overflow/underflow, screen oversize/undersize).
 - Hydrocyclone operating pressure (P).
 - SAG and Ball Mill power draws ($\dot{W}$).
 - SAG and Ball Mill volumetric charge fractions (J).

Optimisation Model Formulation

The calibrated simulation model is embedded within an optimisation framework to identify the best operating conditions.

- **Optimisation Algorithm:** The optimisation was conducted using BO, a method well-suited for computationally expensive, black-box functions like grinding circuit simulations. BO constructs a probabilistic surrogate model of the objective function, updating it after each simulation run

to learn the landscape of the decision variable space. An acquisition function then guides the selection of the next evaluation point by balancing exploitation (sampling where predicted values are high) and exploration (sampling where uncertainty is greatest). After an initial phase of random sampling to seed the surrogate model, the process iteratively selects the point that maximises the acquisition function, runs the simulation, and updates the model. This approach significantly reduces the number of costly evaluations required to reach near-optimal solutions, outperforming traditional methods like grid or random search.

- **Objective Function:** The primary objective is to maximise the hydrocyclone overflow solids throughput (which is equivalent to the plant feed rate at steady-state). As implemented, a penalty term related to constraint violations and the recirculation estimators convergence error is included to ensure stable simulation results.
- **Decision Variables (Inputs):** These are the adjustable parameters manipulated by the optimisation algorithm to find the optimal operating point. They encompass both short-term operational controls and longer-term configuration settings, allowing for a multi-faceted optimisation approach:
 - Short-term Control Variables: Plant feed rate (SAG_F), water addition rates at various points (the SAG feed chute and both pump boxes), and SAG mill rotational speed as a fraction of critical speed (SAG_phi).
 - Medium/Longer-term Configuration Variables: Volumetric fraction occupied by balls in SAG and Ball mills (SAG_JB, BM_JB), hydrocyclone diameters (vortex HC_Do, apex HC_Du), screen design parameters (SC_Gw, SC_h, SC_d, SC_theta), crusher closed-side setting (CR_CSS), Ball mill fraction of critical speed (BM_phi). The specific set of variables included in the optimisation depends on the nature of the optimisation scenario being evaluated, for example control variable setpoint optimisation, or what-if scenario configuration evaluation. Each decision variable is constrained within predefined lower (LB) and upper (UB) bounds reflecting physical or operational limits.
- **Constraints:** Operational and equipment limitations were enforced as constraints using penalty functions added to the objective function value. Penalty factors were tuned heuristically to strongly discourage constraint violations without causing numerical instability during the search. The optimisation ensured adherence to the following key user-specified upper and lower bounds:
 - **Mill Constraints:**
 - SAG Mill Solids Fraction: Maintain appropriate slurry density for transport/trommel
 - SAG Mill Power Draw: Prevent motor overload / inefficient operation
 - SAG Mill Total Charge Volume: Avoid mill overloading or underutilisation which would increase liner wear
 - Ball Mill Power Draw: Prevent motor overload / inefficient operation
 - **Hydrocyclone Constraints:**
 - Operating Pressure: Ensure stable classification and prevent roping/short-circuiting
 - Overflow d80 (Product Quality): Meet downstream process requirements
 - Underflow Solids Fraction: Ensure suitable feed density for the Ball Mill

- **Pump Box Constraints:**
 - Pump Box Solids Fraction: Maintain pumpable slurry density for screen feed

Framework Capabilities and Implementation Considerations

The first-principles digital twin framework presented offers holistic optimisation, capturing complex interactions between unit operations and identifying optimal strategies at the interface of various units, rather than local adjustments common with unit-level control. A key strength lies in its inherent ability to handle constraints; physical limits (e.g., mass/energy balances) are naturally embedded, and operational constraints (e.g., power limits, pressure ranges, product size targets) are incorporated into the optimisation, ensuring recommendations are executable. Furthermore, the modular structure enhances flexibility, allowing the framework to be adapted to different circuit configurations or extended to include upstream (e.g., blasting, blending) or downstream (e.g., flotation) process models.

Realising these benefits, however, necessitates careful consideration of certain implementation aspects. The fidelity and predictive accuracy of the digital twin is highly dependent on the availability of comprehensive, high-quality plant survey data for thorough initial calibration. Moreover, maintaining this accuracy over time requires a commitment to periodic model maintenance and recalibration to account for factors like evolving ore hardness characteristics or gradual equipment wear. Therefore, while the framework provides powerful analytical and optimisation capabilities, its successful deployment hinges on adequate resources for model tuning, robust data acquisition practices, and ongoing model stewardship.

CASE STUDY

The developed digital twin framework was applied to optimise the grinding circuit of a gold processing facility located in West Africa.

Background and Scope

The facility processes gold ore from underground operations, with the comminution circuit, shown in Figure 1, playing a key role in liberating gold before leaching. The circuit includes typical components such as a SAG mill, crusher, vibrating screen, ball mill, and hydrocyclones arranged in a closed-loop configuration. The primary operational objective was to maximise the throughput of solids in the hydrocyclone overflow stream while maintaining product quality and respecting all equipment and process constraints.

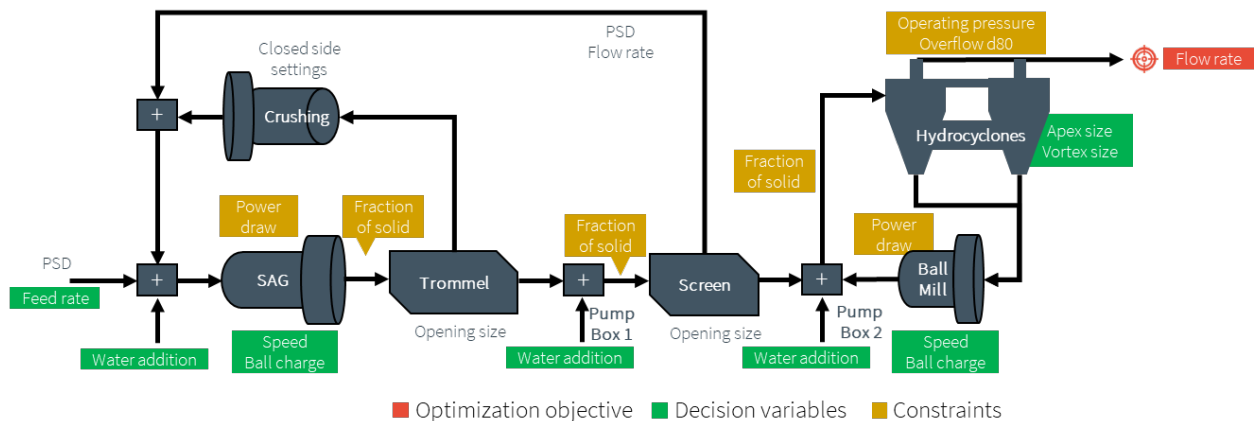


Figure 1. Flowsheet diagram representing the process under which the proposed framework is implemented. Detailing decision variables in green, objectives in red and constraints in orange.

The scope involved developing and calibrating the first-principles digital twin for the comminution circuit described above and subsequently using it within an optimisation framework to identify optimal operational setpoints and assess the impact of potential configuration changes.

The solution utilised the Python-based digital twin framework detailed in Section 2. This included the calibrated unit operation models (SAGM, BLM, TRM, CRM, SCM, HCM), recirculation estimators, KPI calculators (d80M, XPM), and the Bayesian optimisation engine. The framework operated offline, taking current conditions and constraints as input and providing recommended optimal setpoints.

Evaluation KPIs

The primary KPI for optimisation was the hydrocyclone overflow solids mass flow rate (HC_TTPo, t/h). Key performance indicators used for monitoring and constraint checking included:

- Hydrocyclone overflow particle size d80 (HC_do80, mm)
- SAG mill power draw (SAG_Ẇ, kW)
- Ball mill power draw (BM_Ẇ, kW)
- Hydrocyclone operating pressure (HC_P, kPa)
- SAG mill volumetric fill level (SAG_J, %)
- Solids fraction in various streams (PB1_Xp, SAG_Xp, HC_Xu, %)

Model Calibration Approach

The digital twin models were calibrated using detailed survey data collected on February 29th, 2024. This involved tuning model parameters within the process units modules to match measured values of stream flow rates, PSDs (at multiple points in the circuit), mill power draws, hydrocyclone pressure, and solids fractions. Validation plots comparing model predictions against measured data confirmed a generally good fit across the circuit (see Figure 2), providing confidence in the model's predictive accuracy for the baseline conditions.

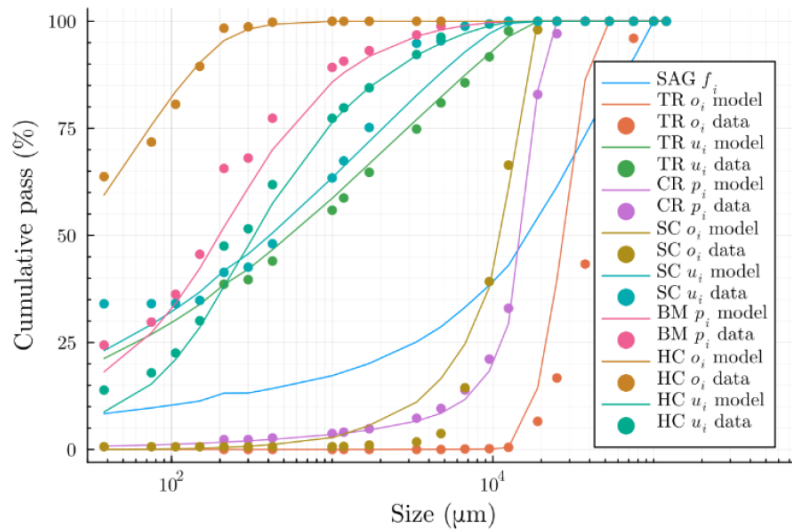


Figure 2. Calibration curve of developed simulation models against the industrial dataset, highlighting model fit to the sampled points.

Some minor discrepancies were observed for the trommel oversize PSD (TR o, low flow rate stream), but this is not worrying because its flow rate is negligible at the current operating conditions (53 t/h, relative to 500-1500 t/h in the other streams). Some abnormal behaviour was also observed for the finest

fractions of the screen undersize, potentially due to sampling/assay error, but it remains small enough to not significantly impact the overall optimisation conclusions.

Results

A reference base case was established using operating conditions aligned with the calibration survey data. This base case operated with a SAG mill feed rate (SAG_F) of 410 t/h, 13 hydrocyclones in parallel ($HC_ncp=13$), a SAG mill speed (SAG_phi) of 73.3% critical, and SAG/Ball mill ball charges (SAG_JB , BM_JB) of 15% and 34% respectively. This resulted in a hydrocyclone overflow throughput (HC_O_oi) of 409 t/h, with a corresponding product size (HC_do80) of 102 μm . Key process variables included SAG power draw (SAG_W) of 1351 kW, ball mill power draw (BM_W) of 3146 kW, and hydrocyclone pressure (HC_P) of 125 kPa.

Scenario evaluation was executed on a workstation (Intel Core i7-10850H @ 2.70GHz, 32GB RAM), a single simulation run of the entire circuit completed in an average of 6 seconds. A full optimisation scenario involving multiple iterations typically completed in an average of 251 seconds, demonstrating practicality for offline daily decision support and infrequent supervisory setpoint optimisation. Three optimisation scenarios were then executed using the calibrated digital twin framework, with a summary of results highlighted in Table I:

- *Scenario 1: Control Variables Optimisation:* The optimiser adjusted only short-term control variables (SAG_F , SAG_Wa , SAG_phi , $PB1_Wa$, $PB2_Wa$), keeping equipment configuration fixed ($HC_ncp=13$, fixed SAG_JB , BM_JB , etc.).
 - *Result:* Achieved a hydrocyclone overflow throughput of 423 t/h, representing a 3.4% increase over the base case. This was primarily achieved by increasing the SAG mill speed (SAG_phi) significantly to 79% of critical and adjusting the water balance (notably higher SAG_Wa). Consequently, SAG power draw (SAG_W) rose to 1526 kW, and hydrocyclone pressure (HC_P) increased to 139 kPa (approaching the upper operating limit). The product size (HC_do80) slightly coarsened to 98 μm , remaining within an acceptable range relative to the typical target.
- *Scenario 2: Control and Configuration Variables Optimisation:* The optimiser adjusted both short-term control variables and key medium-term configuration parameters (SAG_JB , BM_JB), while CR_CSS remained fixed in this run. The number of hydrocyclones remained at 13.
 - *Result:* Achieved a hydrocyclone overflow throughput of 441 t/h, a 7.8% increase over the base case (a further ~4.4% gain over Scenario 1). This improvement was driven by maximising the SAG mill speed (SAG_phi to 80%), and increasing the ball charges in both mills (SAG_JB to 17%, BM_JB to 40%). These changes led to higher power draws (SAG_W at 1609 kW, BM_W at 3354 kW), while hydrocyclone pressure remained high (142 kPa) and product size (HC_do80) stayed at 98 μm . This scenario demonstrates the benefit of adjusting ball loads to support higher tonnage.
- *Scenario 3: Additional Hydrocyclone and Full Optimisation:* This scenario explored a minor design modification by enabling an additional (14th) hydrocyclone ($HC_ncp=14$), while allowing optimisation across control and configuration variables (including water addition points $PB1_Wa$, $PB2_Wa$).
 - *Result:* Achieved a hydrocyclone overflow throughput of 472 t/h, a substantial 15.4% increase over the base case (a further ~7.6% gain over Scenario 2). The key enabler was the increased classification capacity from the fourteenth hydrocyclone, which increased the ball mill circuit capacity. The optimisation maintained high SAG speed (80%) and high ball charges (17% / 40%). Interestingly, the SAG power draw (1571 kW) was slightly lower than Scenario 2 despite higher feed, likely due to optimised water balance (activating $PB1_Wa$, adjusting SAG_Wa and $PB2_Wa$). Ball mill power remained high (3349 kW). Critically, the hydrocyclone pressure (142 kPa) was

maintained within limits despite the significantly higher total flow, as the flow per cyclone was managed by the additional unit. The product size (HC_d80) improved back to 101 μm , comfortably meeting the quality target, and the hydrocyclone underflow density (HC_Xu) reached its upper limit of 84%.

Table I. Summary of Optimisation Scenario Results

Scenario	Optimised Variables	Throughput Increase (vs. Base)	Key Constraint Met (Example: HC d80 $\leq$ 102 μm)
Reference Base Case	Fixed at survey conditions	-	102
#1: Control Optimisation	SAG_F, SAG_Wa, SAG_phi, PB1_Wa, PB2_Wa (13 HCs, fixed config)	3.0%	98
#2: Control & Config Optimisation	Scenario 1 variables + SAG_JB, BM_JB	7.6%	98
#3: Control, Config & +1 Hydrocyclone	Scenario 2 variables + with HC_ncp=14	15.0%	101

Significant throughput improvements were identified, progressing from operational tuning to configuration adjustments and minor design modifications. While this paper's primary objective was throughput maximisation, the framework could readily be adapted to co-optimize or constrain specific energy consumption (kWh/t). Quantification of energy efficiency impacts represents an area for future analysis. These findings confirm the readiness of the digital twin for operational use as an offline advisory tool and provide a strong foundation for transitioning to near real-time deployment.

CONCLUSIONS

Advancements in digital technology are occurring rapidly. We have demonstrated the application of a comprehensive grinding circuit digital twin framework, grounded in first-principles modelling, and BO for the operational improvement at a gold processing facility. By integrating detailed physics-based models of individual unit operations and calibrating them against plant survey data, a high-fidelity virtual replica of the circuit was established. The hybrid nature of the models provided a robust and flexible foundation for simulating and optimising process behaviour in response to variable ore feed PSD and equipment constraints.

The results from three distinct optimisation scenarios were observed, starting with a 3% throughput gain achieved solely by optimising short-term control variables. Incorporating medium-term configuration variables (like mill ball charges) yielded a cumulative gain of 7.6%. The most substantial gain, a 15% increase in throughput relative to the base case, was realised when both operational and configuration variables were optimised alongside a structural change (enabling an additional hydrocyclone). Importantly, across all scenarios, the optimisation respected all specified process and equipment constraints, reinforcing the viability of the recommendations for potential real-world implementation.

Beyond the quantified throughput gains, this paper provides a replicable and technically sound framework for the mining industry. It enables scenario-based planning, allows for the quantitative assessment of the potential economic value of operational changes or design modifications (like adding classification capacity), and supports proactive, data-driven decision-making. The modular architecture of the digital twin allows for relatively seamless extension to include additional processing units or

upstream/downstream integration (e.g., incorporating ore blending strategies or linking to flotation performance models). Its inherent simulation capability supports extensive ‘what-if’ analysis, helping engineers anticipate the impact of ore changes, mitigate potential production risks, and identify future bottlenecks before they materialise. The modular nature of the framework also makes it well-suited for integration with other KPIs, enabling future studies focused on specific energy consumption, or water usage.

Future work will focus on transitioning this offline decision support tool towards an online advisory system integrated with the plant's DCS and potentially leveraging data historians like the PI System. Key challenges for this transition include ensuring real-time data streaming capabilities and establishing robust fail-safe mechanisms and clear operator interface protocols.

APPENDIX A

Abbreviations

Acronym	Definition
<i>AI</i>	<i>Artificial Intelligence</i>
<i>APC</i>	<i>Advanced Process Control</i>
<i>BM</i>	<i>Ball Mill</i>
<i>CR</i>	<i>Crusher</i>
<i>CSS</i>	<i>Closed-Side Setting</i>
<i>d80</i>	<i>Particle diameter at which 80% of material cumulatively passes</i>
<i>DCS</i>	<i>Distributed Control System</i>
<i>HC</i>	<i>Hydrocyclone</i>
<i>JB</i>	<i>Volumetric fraction occupied by balls (charge)</i>
<i>KPI</i>	<i>Key Performance Indicator</i>
<i>ML</i>	<i>Machine Learning</i>
<i>MPC</i>	<i>Model Predictive Control</i>
<i>PB</i>	<i>Pump Box</i>
<i>PID</i>	<i>Proportional-Integral-Derivative</i>
<i>PIML</i>	<i>Physics-Informed Machine Learning</i>
<i>PSD</i>	<i>Particle Size Distribution</i>
<i>RL</i>	<i>Reinforcement Learning</i>
<i>SAG</i>	<i>Semi-Autogenous Grinding</i>
<i>SC</i>	<i>Screen</i>

TR	<i>Trommel</i>
ϕ (<i>phi</i>)	<i>Mill rotational speed as fraction of critical speed</i>

Detailed Model Inputs & Outputs

Table 2: SAG Mill Model (SAGM) Parameters and Variables

Variable Name	Symbol	Category	Unit	Definition/Description
Inputs				
Ore Feed Size Classes	d_i	Calibrated Input/Characterization	mm	Vector defining discrete particle size intervals.
Ore Feed Mass Flow Rate	SAG_F	User-Specified (Scenario Input)	t/h	Total solids mass flow rate fed to the circuit (primary feed).
Feed Ore PSD Fraction	F_i	Calibrated Input/Characterization	-	Fraction of total feed solids (SAG_F) within each size class d_i .
Recirculating Solids Feed PSD	G_{gi}	Internal (from Loop Solver)	t/h	Solids mass flow rate from crusher/screen recycle for each size class d_i .
Feed Water Mass Flow Rate	W_f	Calculated Internally	t/h	Total water entering SAG (from fresh feed moisture + recycle + addition).
Added Water Mass Flow Rate	SAG_W_a	User-Specified (Scenario Input)	t/h	Water added directly to the SAG mill feed.
Recirculating Water Feed	W_g	Internal (from Loop Solver)	t/h	Water mass flow rate from crusher/screen recycle.
Fraction of Critical Speed	SAG_phi (ϕ)	User-Specified (Scenario Input)	-	Mill rotational speed as a fraction of its critical speed.
Volumetric Fraction of Balls	SAG_J_B	User-Specified (Scenario Input)	-	Volume occupied by grinding balls

				relative to total mill volume.
Ore Solid Density	ρ_{os} (ρ_s)	Calibrated Input/Characterisation	t/m ³	Average density of the solid ore particles.
Steel Ball Density	ρ_{ob} (ρ_B)	Static/Design	t/m ³	Density of the grinding media (steel balls).
Mill Geometry (Diameter, Lengths, Trunnion)	d_m, L, L_c, d_t	Static/Design	m	Internal dimensions of the SAG mill shell.
Breakage Rate Parameters	$a_1, a_2, K_1, K_2, \mu, \lambda$	Calibrated	various	Coefficients defining the energy-normalised breakage rate function (siE).
Discharge Classification Parameters	d_{50c}, m	Calibrated	mm, -	Parameters defining the grate/discharge classification function (ki).
Discharge Model Parameters	$k_{prime}, m_2, dg, \gamma, A$	Calibrated	various	Parameters for the Napier-Munn discharge flow model.
Charge Porosity	ϵ (ϵ)	Calibrated/ Assumed	-	Effective void fraction within the mill charge.
Power Draw Model Coefficient	KW_d (K_W)	Calibrated	kW/(t ^{1/3} m)	Coefficient relating mill size, load, and speed to power draw.
Euler Integration Parameters	$TOL_EULER, DELTA_T_EULER, MAXITER_EULER, AASYMP$	Static/Solver Setting	-	Parameters controlling the numerical solver for mill holdup.
Outputs				
Product Solids Mass Flow Rate per Size Class	P_{pi}	Output	t/h	Solids mass flow rate exiting the mill for each size class di.

Product Water Mass Flow Rate	W_p	Output	t/h	Water mass flow rate exiting the mill.
Volumetric Fraction of Total Charge	J	Output	-	Volume occupied by total charge (ore+balls+slurry) relative to mill vol.
Mill Power Draw	$\dot{W}$ (W)	Output	kW	Calculated electrical power consumed by the mill motor.
Holdup Convergence Error	dhx	Output (Solver Diagnostic)	various	Residual error from the Euler integration for steady-state holdup.

Table 3. Ball Mill Model Parameters and Variables

Parameter/Variable Name	Symbol	Category	Unit	Definition/Description
Inputs				
Ore Feed Size Classes	d_i	Calibrated Input/Characterisation	mm	Vector defining discrete particle size intervals.
Solids Feed PSD	F_{fi}	Internal (from Hydrocyclone U/F)	t/h	Solids mass flow rate from hydrocyclone underflow for each size class d_i .
Water Feed Mass Flow Rate	W_f	Internal (from Hydrocyclone U/F)	t/h	Water mass flow rate from hydrocyclone underflow.
Fraction of Critical Speed	BM_phi (ϕ)	User-Specified (Scenario Input)	-	Mill rotational speed as a fraction of its critical speed.
Volumetric Fraction of Balls	BM_JB	User-Specified (Scenario Input)	-	Volume occupied by grinding balls relative to total mill volume.
Ore Solid Density	ρ_{os} (ρ_s)	Calibrated Input/Characterisation	t/m ³	Average density of the solid ore particles.
Steel Ball Density	ρ_{oB} (ρ_B)	Static/Design	t/m ³	Density of the grinding media (steel balls).
Mill Geometry (Diameter, Lengths, Trunnion)	dm, L, L_c, dt	Static/Design	m	Internal dimensions of the ball mill shell.

Energy-Normalised Breakage Rate Params	$S1E, d_{ref}, \zeta_1$	Calibrated	various	Coefficients defining the energy-normalised breakage rate function (siE).
Charge Porosity	ϵ	Calibrated/Assumed	-	Effective void fraction within the mill charge.
Power Draw Model Coefficient	KWd (K_W)	Calibrated	$kW/(t\sqrt{m})$	Coefficient relating mill size, load, and speed to power draw.
Outputs				
Product Solids Mass Flow Rate per Size Class	P_{pi}	Output	t/h	Solids mass flow rate exiting the mill for each size class d_i .
Product Water Mass Flow Rate	W_p	Output	t/h	Water mass flow rate exiting the mill.
Mill Power Draw	$\dot{W}$ (W)	Output	kW	Calculated electrical power consumed by the mill motor.
Volumetric Fraction of Total Charge	J	Output	-	Volume occupied by total charge (ore+balls+slurry) relative to mill vol.

Table 4. Hydrocyclone Model Parameters and Variables

Parameter/Variable Name	Symbol	Category	Unit	Definition/Description
Inputs				
Ore Feed Size Classes	d_i	Calibrated Input/Characterisation	mm	Vector defining discrete particle size intervals.
Solids Feed PSD	F_{fi}	Internal (from Pump Box 2)	t/h	Solids mass flow rate from PB2 for each size class d_i .
Water Feed Mass Flow Rate	W_f	Internal (from Pump Box 2)	t/h	Water mass flow rate from PB2.
Number of Cyclones in Parallel	HC_{ncp}	Static/Design or Scenario Input	-	Number of identical hydrocyclones operating.
Overflow Nozzle Diameter (Vortex Finder)	HC_{Do}	User-Specified (Scenario Input)	cm	Diameter of the overflow outlet.
Underflow Nozzle Diameter (Apex)	HC_{Du}	User-Specified (Scenario Input)	cm	Diameter of the underflow outlet.

Ore Solid Density	ρ_{os}	Calibrated Input/Characterisation	t/m^3	Average density of the solid ore particles.
Cyclone Diameter	D_c	Static/Design	cm	Main cylindrical diameter of the hydrocyclone body.
Free Vortex Height	h	Static/Design	cm	Height of the free vortex zone within the cyclone.
Feed Nozzle Diameter	D_i	Static/Design	cm	Diameter of the tangential feed inlet.
Liquid Density	ρ_{ol}	Static/Assumed	t/m^3	Density of the carrier fluid (water).
Liquid Viscosity	η	Static/Assumed	cP	Viscosity of the carrier fluid (water) at a reference temperature.
Plitt Model Calibration Parameters	$F1, F2, F3, F4$	Calibrated	-	Empirical coefficients for the Plitt hydrocyclone model equations.
Outputs				
Overflow Solids Mass Flow Rate per Size Class	O_{oi}	Output	t/h	Solids mass flow rate exiting via overflow for each size class d_i .
Underflow Solids Mass Flow Rate per Size Class	U_{ui}	Output	t/h	Solids mass flow rate exiting via underflow for each size class d_i .
Overflow Water Mass Flow Rate	W_o	Output	t/h	Water mass flow rate exiting via overflow.
Underflow Water Mass Flow Rate	W_u	Output	t/h	Water mass flow rate exiting via underflow.
Operating Pressure Drop	P	Output	kPa	Pressure difference between feed and overflow/underflow.
Parameter S (Related to Water Split)	S	Output (Intermediate Calc)	-	Intermediate parameter in Plitt model related to water split to underflow.

Table 5. Crusher Model Parameters and Variables

Parameter/Variable Name	Symbol	Category	Unit	Definition/Description
Inputs				
Ore Feed Size Classes	d_i	Calibrated Input/Characterisation	mm	Vector defining discrete particle size intervals.
Total Solids Feed Rate	F	Internal (from Trommel O/S)	t/h	Total solids mass flow rate fed to the crusher.
Solids Feed PSD Fraction	f_i	Internal (from Trommel O/S)	-	Fraction of total feed solids (F) within each size class d_i .
Solids Fraction in Feed	X_f (χ_f)	Internal (from Trommel O/S)	-	Mass fraction of solids in the crusher feed stream.
Closed Side Setting	CR_CSS	User-Specified (Scenario Input)	mm	Minimum discharge opening of the crusher.
Classification Function Parameters	α (a), β (β), γ (γ), k_3	Calibrated	mm, mm, mm, -	Parameters defining the probability of a particle passing the CSS.
Breakage Function Parameters	K , m , nc (n)	Calibrated	-, -, -	Parameters defining the distribution of progeny particles after breakage.
Outputs				
Product Solids Mass Flow Rate per Size Class	P_{pi}	Output	t/h	Solids mass flow rate exiting the crusher for each size class d_i .
Product Water Mass Flow Rate	W_p	Output	t/h	Water mass flow rate exiting the crusher (assumed same as feed water).

Table 6. Screen & Trommel Model Parameters and Variables

Parameter/Variable Name	Symbol	Category	Unit	Definition/Description
Inputs				
Ore Feed Size Classes	d_i	Calibrated Input/Characterisation	mm	Vector defining discrete particle size intervals.
Solids Feed PSD	F_{fi}	Internal (from Pump Box 1)	t/h	Solids mass flow rate from PB1 for each size class d_i .
Water Feed Mass Flow Rate	W_f	Internal (from Pump Box 1)	t/h	Water mass flow rate from PB1.
Water Addition Gain (Spray Water)	SC_{Gw}	User-Specified (Scenario Input)	t/h per t/h solid	Rate of spray water added per tonne of solids feed (Karra model input).
Screen Aperture Opening	SC_h	User-Specified (Scenario Input)	mm	Nominal opening size of the screen mesh.
Wire Diameter	SC_d	User-Specified (Scenario Input)	mm	Diameter of the screen wires.
Screen Deck Inclination Angle	SC_{θ} (θ)	User-Specified (Scenario Input)	°	Angle of the screen deck relative to horizontal.
Number of Screens in Parallel	SC_{ncp}	Static/Design	-	Number of identical screens operating.
Ore Solid Density	ρ_{os} (ρ_s)	Calibrated Input/Characterisation	t/m ³	Average density of the solid ore particles.
Karra Model/Classification Parameters	α (a), β (β), a_1, b_1, c_1, a_2, c_2	Calibrated	various	Empirical parameters for the Karra screening efficiency model.
Oversize Solids Fraction	X_o (χ_o)	Calibrated/Assumed	-	Target/Assumed solids mass fraction in the oversize stream (for water split).
Deck Dimensions	L_1, L_2	Static/Design	m	Width and length of the screen deck (used to calculate area sqm).
Outputs				

Oversize Solids Mass Flow Rate per Size Class	O_{oi}	Output	t/h	Solids mass flow rate exiting via oversize for each size class d_i .
Undersize Solids Mass Flow Rate per Size Class	U_{ui}	Output	t/h	Solids mass flow rate exiting via undersize for each size class d_i .
Oversize Water Mass Flow Rate	W_o	Output	t/h	Water mass flow rate exiting via oversize.
Undersize Water Mass Flow Rate	W_u	Output	t/h	Water mass flow rate exiting via undersize.

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Advancing geotechnical risk management in mining with spatially-enabled and process-driven information systems

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Most large open pit mines currently employ risk management concepts which are aimed at the anticipation of slope instability, provided that the risk of expected events is tolerable, adheres to industry and company geotechnical standards, as well as being controllable. In order to facilitate this outcome in an increasingly complex mining environment, geotechnical engineering aspects including slope design (stability analysis and geotechnical risk assessment), waste dump risk management, mine to design compliance and blasting performance, slope performance (bench, stack and overall), mine dewatering/depressurisation and slope monitoring need to be managed effectively. Therefore, the accurate measurement/verification and detailed analysis of the correct parameters and safety controls are essential. Information management systems play a key role in supporting decision-making in the geotechnical risk management process through the conversion of data into information, empowering specialists with knowledge to make informed decisions. The successful implementation of information management systems in Anglo American are discussed, focussing on processes, people, and technology. The integration of various data sources, geotechnical analysis and outputs on an information management system is critical to actively manage fall of ground hazards as they materialise in a dynamic rock mass and mining environment. The collaboration between geotechnical engineering, systems engineering and various other mining disciplines is key to facilitate the integration of technology and process-driven information management strategies. Ultimately it sets a robust foundation for sustainable and effective geotechnical risk management.

INTRODUCTION

Background

Most large open pit mines employ the concept of 'slope management,' which focuses on anticipating slope instability and ensuring that the associated risks are justifiable, controllable, and aligned with industry and company standards. Effective slope management requires the careful coordination of various operational geotechnical engineering aspects, including controlled limit blasting, mine dewatering and/or depressurisation, mine to design performance, slope performance verification at the bench, stack, and overall scale, as well as critical slope monitoring and fall of ground (FOG) hazard management to ensure safety of personnel.

Problem Statement

In increasingly complex mining environments, effective geotechnical risk management is critical to prevent uncontrolled slope instability and ensure operational safety. Current practices often struggle to integrate diverse data sources and analyses efficiently, making it difficult to manage dynamic geotechnical hazards in real-time. There is therefore a need for process-driven, spatially-enabled information systems to enhance decision-making and improve the proactive management of geotechnical risks.

Objective

This paper aims to demonstrate how process-driven and spatially-enabled information systems can enhance geotechnical risk management in the modern mining world.

GEOTECHNICAL RISK MANAGEMENT IN MINING

Risk Management Principles

The principles of safety process risk management are crucial for ensuring safe and sustainable operations in industries dealing with hazardous processes. The Centre for Chemical Process Safety (CCPS), in its widely recognised publication *Guidelines for Risk-Based Process Safety* (2007), provides a foundational framework for managing process safety risks. This comprehensive guide details the principles and practices necessary for organisations to effectively anticipate, manage, and mitigate process safety risks. The risk-based approach outlined by CCPS has been adopted across various industries, offering a structured methodology for maintaining safe operations.

Another key reference in the development of process safety management principles is the American Petroleum Institute's *Recommended Practice 750: Management of Process Hazards* (1990). This document lays the groundwork for managing process safety hazards, particularly within the oil and gas industry, and has influenced the development of subsequent safety management systems. Together, these references have become central to the understanding and implementation of process safety risk management and are extensively cited in both academic and industrial literature.

Elimination of Uncontrolled Falls of Ground

In the mining industry, particularly in geotechnical engineering, the principles of safety process risk management can be applied to ensure stable, safe, and sustainable operations in highly complex, dynamic and potentially hazardous environments. Drawing on methodologies from process safety frameworks discussed in the previous section, a structured approach to identifying, assessing, and mitigating geotechnical risks has been developed. Originally designed for the chemical and oil industries, these principles have been adapted to address the unique challenges of mining operations, particularly in relation to slope stability, ground control, and the prevention of uncontrolled FOG incidents. By applying a risk-based approach, the goal is not only to enhance operational safety but also to improve long-term financial sustainability and environmental responsibility.

The Risk-Based Safety Management System is built on four key pillars that provide a structured framework for maintaining safety and operational excellence in hazardous environments. These pillars are designed to help the organisation to anticipate, manage, and mitigate risks effectively, ensuring long-term stability, safety, and sustainability (refer to Figure 1).

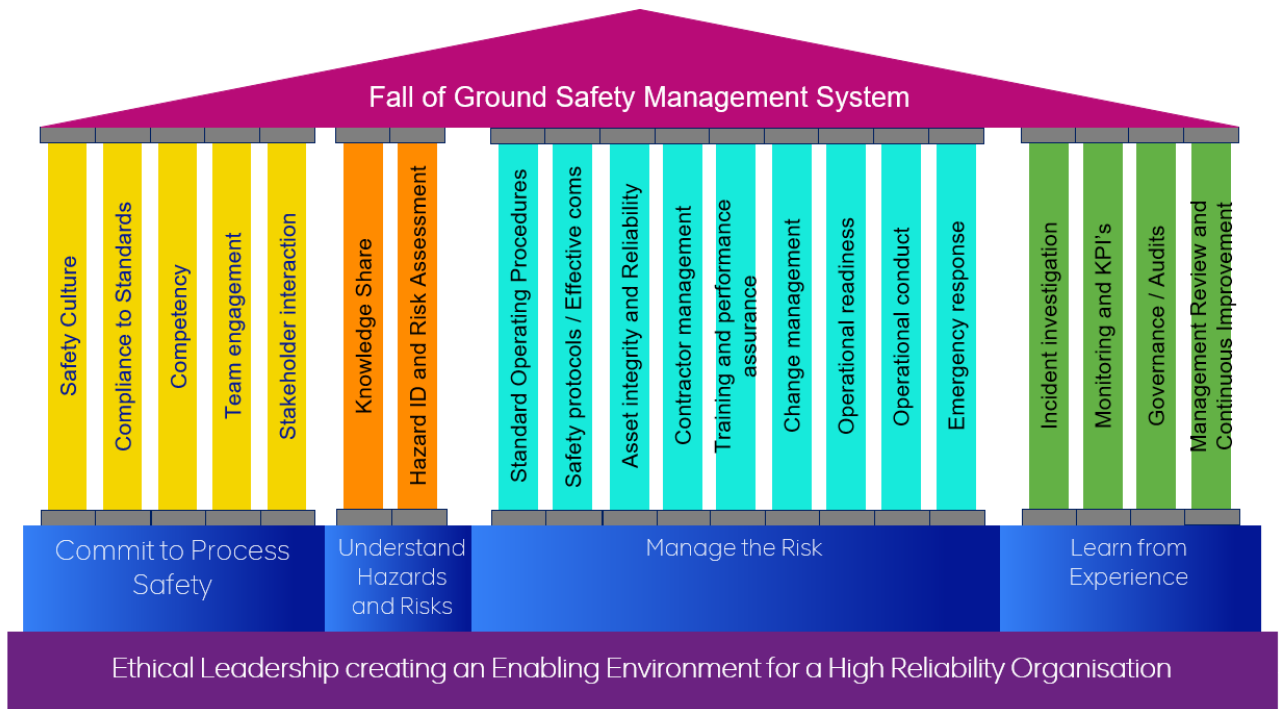


Figure 1. Adaptation of the risk-based process safety framework for fall-of-ground safety management in mining. (Modified after CCPS Guidelines for Risk Based Process Safety, 2007.)

Commitment to Safety

The cornerstone of process safety is an unwavering commitment to safety as a core organisational value in the company. The workforce is convinced the organisation fully supports safety as a core value and will tend to do the right things, in the right ways, at the right times — even when no one else is looking.

Anglo American has established a comprehensive but concise Geotechnical Standard for Mining applicable to both surface and underground operations. This standard defines the minimum requirements necessary to eliminate uncontrolled FOGs and reduces the risk of FOG incidents and fatalities. It is underpinned by a parent bowtie risk assessment which outlines the minimum mandatory critical controls that must be implemented across all Anglo American mining operations to ensure consistent adherence to safety protocols.

Understand Hazards and Risk

A deep understanding of hazards and risks forms the foundation of a risk-based approach. In the mining geotechnical engineering context, this includes detailed assessment of potential FOG risk. By accurately identifying all ground-related hazards and quantifying these risks, mining operations can allocate resources effectively to implement adequate and effective controls, such as real-time monitoring systems for early detection of slope failures or designing appropriate ground control measures to mitigate risks.

Manage the Risk

Effective risk management requires continuous effort to control and mitigate identified risks, if it is not possible to eliminate the hazard. This includes maintaining ground control processes within defined risk tolerances, regularly updating procedures in response to changes in rock mass or mining conditions and being prepared to manage incidents when they occur. By leveraging a thorough understanding of risks, operations can better handle the resultant hazards and, in turn, sustain long-term, accident-free, and profitable operations.

Learn from Experience

The fourth pillar of the risk management system focuses on learning from experience, with a commitment to continuously improve by analysing past FOG incidents to enhance future safety performance. To facilitate this, a spatially-enabled database that captures comprehensive geotechnical data for each incident was developed. This system is further supported by a decision tree, aligned with the company FOG reporting framework, which classifies incidents based on criteria such as controlled, uncontrolled, significance, and reportability. This classification enables trend analysis to identify where controls may have failed. Notably, even if a preventative control fails, an incident can still be averted by mitigation controls – such as slope radar monitoring – which can remove personnel from hazardous areas in time. However, if any control fails, an internal investigation must be conducted to identify and close out any gaps.

Together, these pillars form a comprehensive and effective approach for not only safeguarding people and assets, but also enable maximum value from the operation.

INFORMATION MANAGEMENT SYSTEMS IN GEOTECHNICAL RISK MANAGEMENT

Role of information Management Systems

The accurate measurement and detailed analysis of the correct geotechnical and operational parameters are essential. Information management systems play a key role in supporting decision-making in the slope management process through the conversion of data into information, empowering specialists with knowledge to make informed decisions.

Data collection and integration

It is important that various data sources – for example geological, structural, rock mass and hydrogeological data, geotechnical analyses and risk assessment information, mine planning information, operational performance data and slope performance monitoring data – be integrated on an information management system to actively manage geotechnical hazards as they materialise in a dynamic rock mass and mining environment. The collaboration between geotechnical engineering, processes/systems engineering and various other mining disciplines; including new technologies and methodologies, is key to manage geotechnical risk effectively.

Transforming Data into Knowledge for Effective Communication

In the context of FOG risk management, effective communication is paramount. Clear, timely and accurate information sharing ensures that everyone involved – whether on-site or in support roles – understands the hazards, mitigation strategies, and safety protocols. This reduces the likelihood of accidents by promoting awareness and adherence to safety measures and controls, such as respecting ‘No-Go Zones’ and responding appropriately to changing hazard conditions. Without effective communication, even the best-designed safety systems can fail to protect workers, equipment, and operations. It is a critical element that bridges technical solutions with real-world application.

PEOPLE, PROCESSES, AND TECHNOLOGY: A COLLABORATIVE APPROACH

The Role of Geotechnical Engineering Teams

In the 1980s, the concept of high reliability organisations (HROs) was pioneered by researchers such as Karl E. Weick, Kathleen M. Sutcliffe, and David D. Woods. Their work focused on organisations that operate in complex, high-risk environments – such as nuclear power plants and air traffic control – yet manage to maintain remarkably low failure rates. The principles they developed emphasise the importance of organisational resilience, attention to failure, and a commitment to reliability, making them widely applicable across various sectors, including geotechnical engineering (Weick & Sutcliffe, 2001).

The framework of HROs in a geotechnical engineering context emphasises several key principles to ensure effective teamwork to achieve safety and reliability (Figure 2).

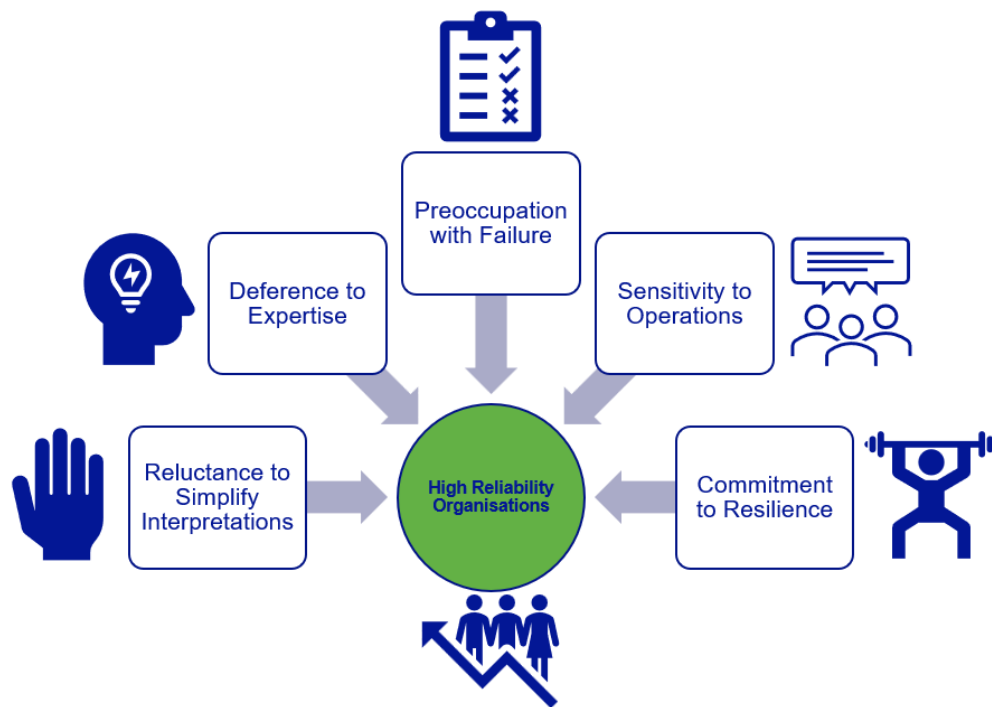


Figure 2. The five key principles of high reliability organisations (after Weick & Sutcliffe, 2001).

- Preoccupation with Failure**
 The team maintains a mindset of chronic unease, constantly thinking about what could go wrong. Every new bench or exposed development is carefully mapped and assessed to verify that the design remains valid, for all four aspects of the geotechnical model on which the design is based. Critical controls are continuously monitored to ensure their effectiveness, and geotechnical engineers embrace the idea that ‘all models are wrong, some are just more useful,’ highlighting the importance of constant vigilance.
- Deference to Expertise**
 Decisions are deferred to individuals with the most relevant experience and expertise, particularly those who are closest to the problem. Frontline personnel are actively engaged, and their inputs are sought to inform decisions. Hierarchies do not interfere with trusting the expertise of those who know the rock mass and operations best.
- Sensitivity to Operations**
 Awareness of the specific challenges at a particular operation is essential to recognising and addressing anomalies and/or deviations. The team fosters a genuine interest in understanding the unique context of each operation in terms of setting, size, complexity, and culture. Actively engaging operational teams helps mitigate potential constraints that could affect the accurate execution of geotechnical designs.
- Reluctance to Simplify Interpretations**
 While simplicity has its elegance, the team avoids oversimplifying models and designs. Critical parameters and the variability inherent in them are carefully considered to justify engineering judgements. The illusion of control (wanting to believe we are in control) is scrutinised, acknowledging that uncertainty is a constant factor in mining geotechnical engineering, and care is taken not to assume control when it may not exist, because the illusion of control is more persuasive than the reality of uncertainty.

- **Commitment to Resilience**

The team is committed to understanding, recovering, and learning from errors and incidents. Personnel are encouraged to swiftly learn from events, anticipate variability, and remain adaptive to change. Lessons learned are openly shared, and while data is protected, it is made accessible for broader learning. This commitment helps the team continuously improve and become more resilient to future challenges.

Systems Engineering and Process Integration

Effective systems engineering focuses on creating an integrated approach that ensures all parts of a system work seamlessly together, reducing inefficiencies and communication gaps across departments (Blanchard & Fabrycky, 2010). In the context of mining, integrating geotechnical data into mine planning and operations is critical for ensuring stability, safety, and operational efficiency.

PROCESSES

When developing an information system, it is crucial to adopt certain principles and frameworks that ensure the system aligns with organisational goals and promotes efficiency. These approaches not only improve functionality but also ensure the system evolves effectively with user needs and operational demands. They are:

1. **Ensure alignment of Process to Standards:**

It is crucial to align each process or workflow with company and industry standards, ensuring that no incorrect or immature processes are captured or systemised. This helps maintain consistency and the required standard.

2. **Build Measure Learn Cycle:**

Following the iterative Build → Measure → Learn cycle is a powerful tool for improving the system (Ries, 2011). This approach involves:

- Building systems that can integrate geotechnical data into mine planning and operations.
- Measuring outcomes such as safety performance, operational efficiency, and system robustness.
- Learning from these results to make data-driven decisions and refine the processes continuously.

3. **SCRUM Methodology:**

Using SCRUM principles, small, cross-functional teams can focus on incremental improvements, adapting as new data is gathered. This agile approach allows for quicker response times and improved coordination across departments (Schwaber & Sutherland, 2020).

Systems Engineering and Geotechnical Data Integration

Systems engineering plays a vital role in facilitating the integration of geotechnical data into mine planning and operational processes by:

- Establishing a framework that ensures different departments (geotechnical, survey, operational, planning) can share data and communicate effectively.
- Creating data-driven decision-making workflows that leverage the latest geotechnical information.
- Enabling automated or semi-automated processes that adapt based on real-time geotechnical conditions, enhancing mine planning flexibility and operational safety.

Through these integrated processes, mining operations can significantly reduce risk, improve decision-making, and ensure that all departments are aligned with both operational goals and safety standards.

Technological Advancements

The integration of modern information systems, along with the use of drone and satellite imagery provided by Survey, has revolutionised remote geotechnical inspections and risk control assessments. Geotechnical engineers and strata control officers can now conduct more efficient inspections remotely, significantly reducing the need for frequent pit visits (Figure 3). This not only enhances safety by minimising exposure to hazardous environments but also allows teams to focus their on-site efforts on high-risk areas. Moreover, the development of digital polygons for FOG zones of influence, for example, is paving the way for advanced geofencing capabilities. When integrated with existing vehicle management systems, this technology can soon provide real-time warnings to personnel, instructing them to vacate 'No Go' zones as defined, further bolstering safety and risk management in mining operations.

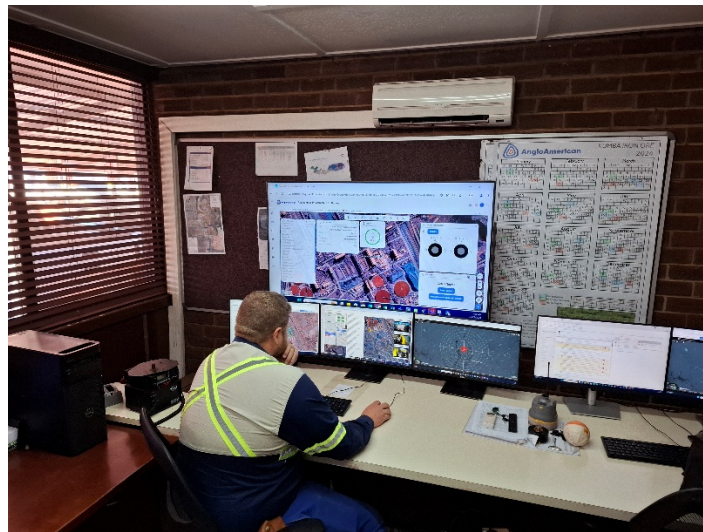


Figure 3. Drone flight control from the Sishen survey office.

CASE STUDY: IMPLEMENTATION OF GEOTECHNICAL ENGINEERING INFORMATION MANAGEMENT SYSTEMS

Overview of Implementation

The successful implementation of a global information management system supporting mine waste dump and stockpile management is discussed by Bester, *et al.*, (2022), focussing on processes, people, and technology. As waste dump and stockpile risk management data is published on the internet by ArcGIS enterprise as a feature service, the data is accessible to any authorised application capable of harvesting web-based feature services. ArcGIS Server supports all the open data sharing standards, allowing other supporting applications to share information.

The objective of the system is to make it as easy as possible for operational personnel to capture all relevant waste dump and stockpile information, following international guidelines by Hawley (2017). For this reason, using the ArcGIS Enterprise licence agreements in Anglo, all a user requires is a web browser with access to the Anglo American server (domain). Using the mine waste dump and stockpile template in Smart Editor, it is very quick and easy for site teams to create/digitise new features in the system. All relevant information required is assisted with full description domain lists (lookups), where possible, to enable easy data capture. Where required, factors are automatically calculated by attribute rules which have been added to the database structure.

The system, which can be accessed from anywhere, has been designed with four levels of access to enable support of Anglo American global mining activities. At mine level, personnel can only access their own data. At the next higher level, all data for mines in a specific business unit can be accessed. At the corporate level, all Anglo American information is accessible. However, the system is flexible, and access can be easily provided as required. The highest level is the system administration level, where the system is administrated, monitored, and maintained (Bester *et al.*, 2022).

For reporting purposes, customisable dashboards indicating status of dumps, risk levels or any other relevant information were created. All captured data is dynamically updated, ensuring that charts and dashboard show the latest information (Figure 4). The dashboards are also aggregated from Mine Level to Business Unit Level and to Corporate Level. Information is periodically updated with a management dashboard to track and ensure the accuracy and completeness of information. Document management functionalities that link to Sharepoint are also included in the system to ensure storage of all relevant information, for example design and associated material characterisation reports, photographs etc.

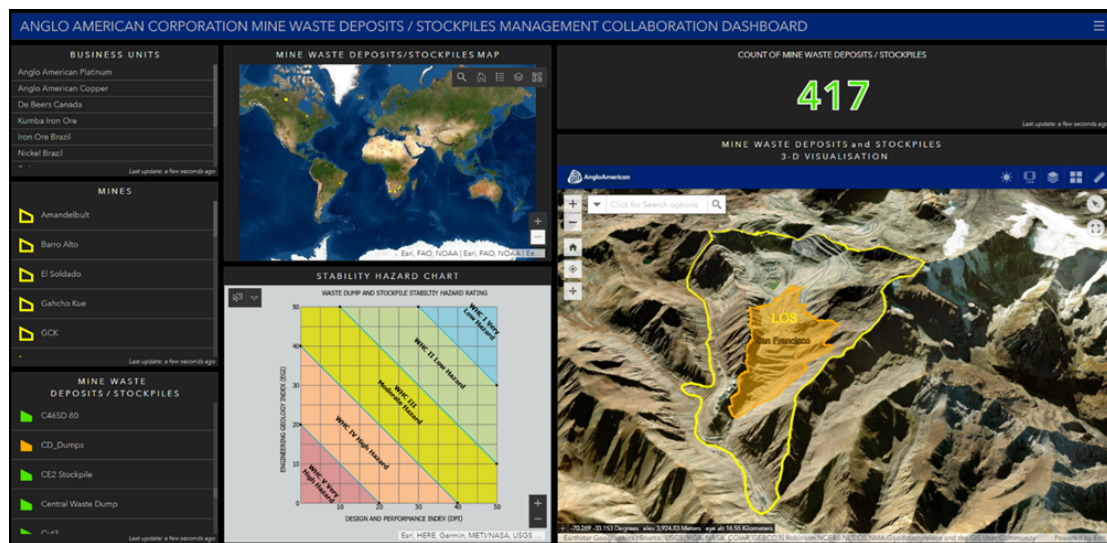


Figure 4. Example of GIS dashboard for waste dumps (rating data was removed for illustration purposes) (Bester *et al.*, 2022).

Geotechnical hazard management forms part of the Ground Control Management Plan that supports the Mine plan, following a risk-based approach. This is aligned with the elimination of fatalities strategy in Anglo American and is based on the principle that implemented controls are adequate in design and are verified for effectiveness on a regular basis.

The process aims to identify and mitigate any deviations and/or anomalies, as well as to support operational teams in the prevention of uncontrolled FOGs. Ground-related hazard management is usually legally mandated by law in most jurisdictions, and requirements are stipulated in the Geotechnical Standard for Mining. Having a robust process in place is therefore critical to deliver a Mine plan that has acceptable geotechnical risk and can deliver its objectives.

A review of this process, supported by the development of a Live Hazard Map in GIS, was implemented by the geotechnical teams at Sishen, Kolomela, Mogalakwena and Amandelbult open pits.

The Geotechnical Engineering Information Management System is also hosted on the Anglo network in the Azure cloud, utilising an SQL database that ensures full ownership of data is retained. Figure 5 shows the high-level system architecture that comprises a mobile application and a GIS frontend (web apps).

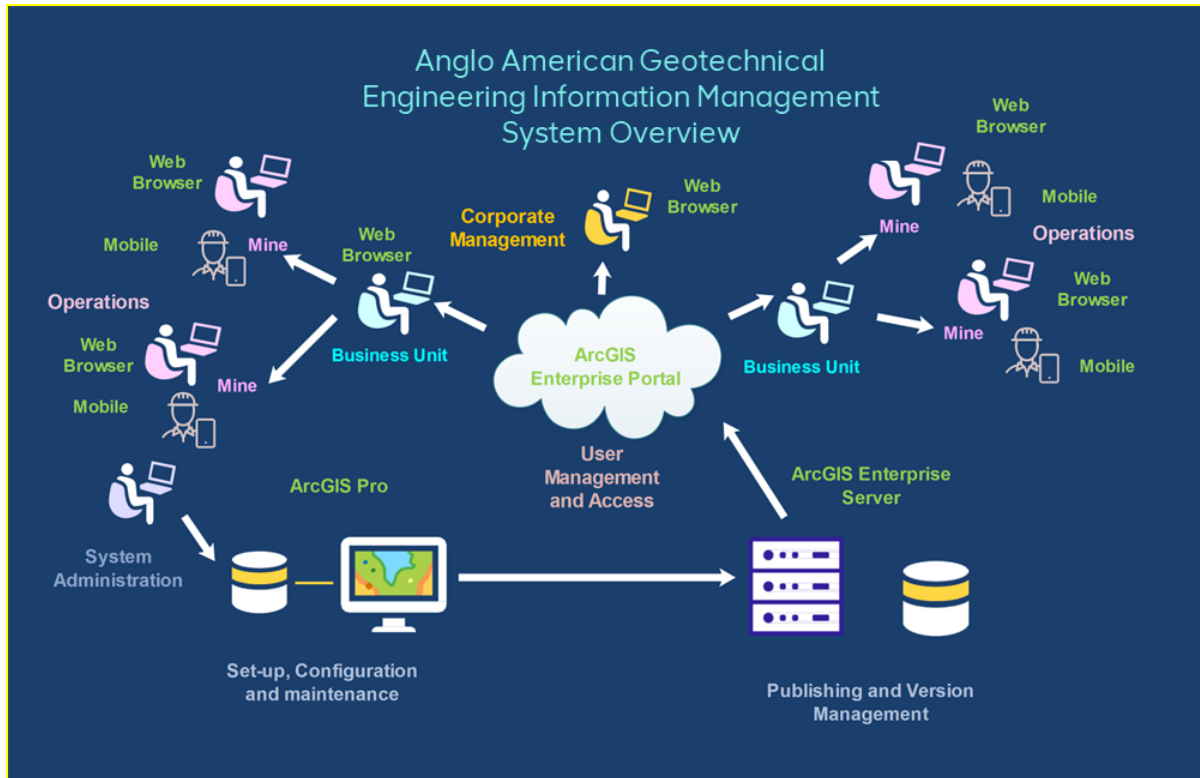


Figure 5. System overview and high-level architecture.

It adheres to all company Information Management security protocols. Furthermore, a no-code/low-code approach was followed, prioritising configuration over hard coding to facilitate in-house support and adaptability / flexibility. As the data is published on the internet by ArcGIS enterprise as a feature service, the data is accessible to any authorised application capable of harvesting web-based feature services. ArcGIS Server supports all the open data sharing standards, allowing other supporting applications to share information. This allows authorised systems to share data in a loosely coupled architecture.

The Live Hazard Map module was designed to be flexible; for example, it follows and supports the practical hazard management workflow in operations, because the development team believes that: 'Software must be on your way, not in your way or out of your way'.

Key Challenges and Solutions

During the initial stages of development, the team identified significant limitations in producing existing hazard maps. Most hazard maps were manually updated on a monthly basis, which often rendered them outdated and inadequate for addressing the rapidly evolving conditions of a dynamic mining environment. Furthermore, workflows between operations were found to be inconsistent and the maps frequently included excessive and, at times, irrelevant information, leading to unnecessary complexity.

Interviews conducted with frontline production personnel revealed that a considerable proportion of these individuals found the hazard maps unclear and ineffective in communicating specific actions required for mitigating risks. This feedback underscored a critical gap in the design and utility of hazard maps, highlighting the need for a more streamlined, actionable, and real-time approach to hazard communication to support operational and safety objectives effectively.

Following modern cybersecurity rules and managing the information management protocols of a large organisation brought challenges, such as delays in workflows due to strict data access and sharing policies. The need for extensive approvals, audits, and user training further slowed progress and limited

flexibility. While the team understood that these measures are essential for security and compliance, they required careful balancing to meet operational needs without compromising security protocols and governance.

The Geotechnical Risk Management system was developed to provide real-time hazard maps that systematically track the lifecycle of FOG-related hazards. This system leverages a GIS-based spatially enabled interface as the front end, integrated with a SQL database to manage and analyse geotechnical data efficiently. The process steps are as follows; illustrated in Figure 6.

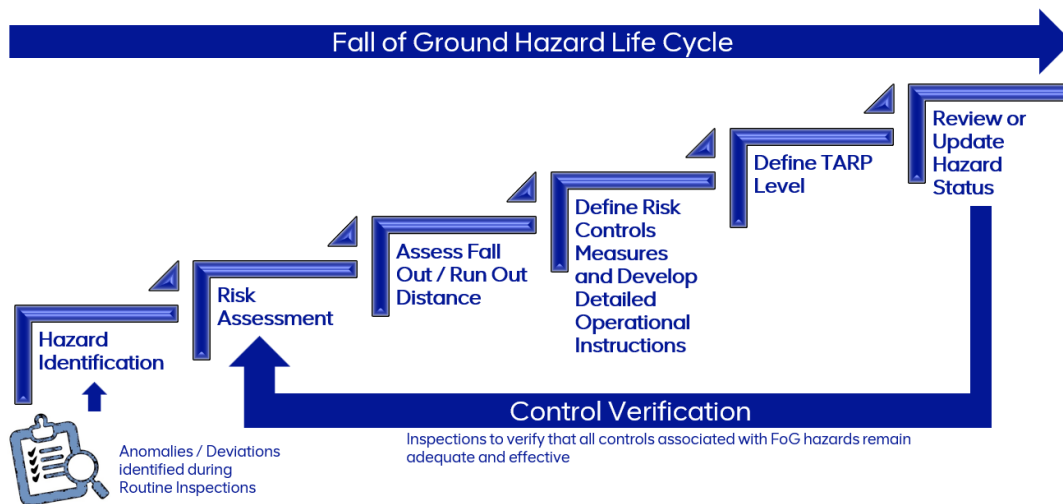


Figure 6. Fall of ground hazard life cycle.

Hazard Identification

Classify the hazard as a potential rock fall, single-, multiple bench failure/overall slope failure / subsidence.

Step 2: Risk Assessment

Utilise the Anglo Risk matrix to determine unmitigated risk for safety as well as other consequences such as financial for the unwanted event: uncontrolled FOG.

Step 3: Assess fall Out / Run Out distance

Assess fallout distance for rockfall hazards and runout distance for slope failure hazards to digitally map the zone of influence for each hazard. This enables the classification of 'No-Go Zones'. These are areas where access must be restricted for safety.

Step 4: Define Risk Control Measures and Develop Detailed Operational Instructions

Collaborate with production personnel to define and implement the controls required to maintain safe production.

Step 5: Define the TARP Level

The geotechnical engineer sets the Trigger Action Response Plan (TARP) level dependent on control status; therefore, the defined controls must be adequate in design and effectively implemented and functioning (Figure 7).

RANKING	PRIORITY	ACTION	DESCRIPTION
High	Stop & Fix	Controls are not in place and current control strategy will not function as intended	The situation must be rectified immediately. Stop work, implement interim controls, and implement controls to lower the risk
Medium	Fix within Shift	Control strategy is in place with gaps in other levels of controls such that the overall control strategy is unlikely to function as intended	The situation must be rectified urgently. Prioritise work required to execute identified controls
Low	Fix within Schedule	The overall control strategy is expected to function as intended with no immediate risk on the PUE, minor gaps exist on other levels of control.	Action to commence within a short-term schedule informed by mining plan, exposure
Mitigated	Normal operating conditions	Controls are in place; the control strategy is functioning as intended	No specific action is required, continue implementing the day-to-day standard operating procedures and controls

Figure 7. Example of a generic Trigger Action Response Plan.

Step 6: Review or update the Hazard Status

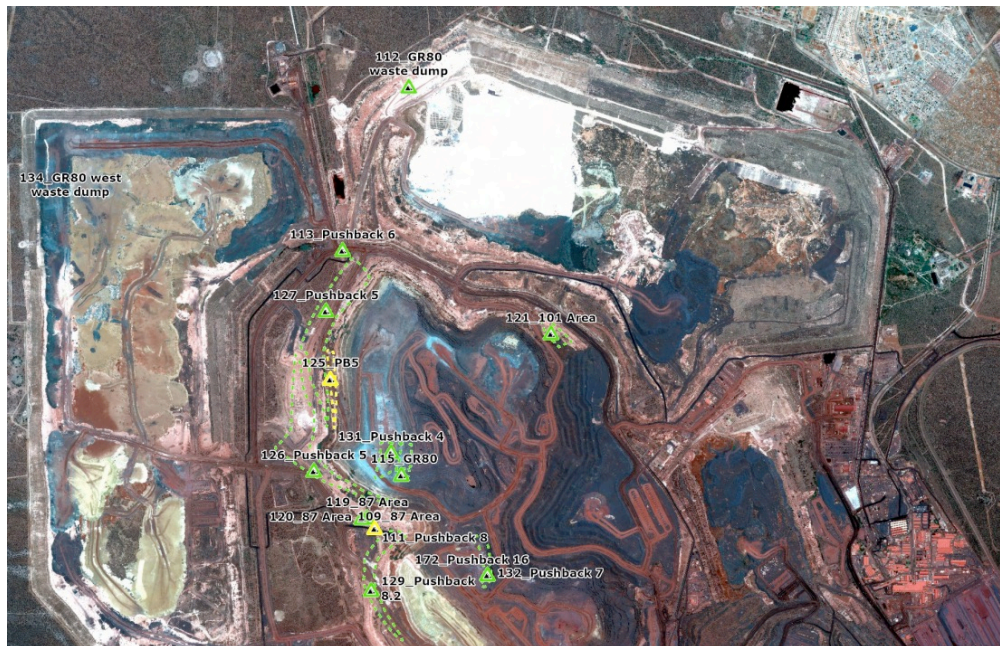
Maintain a comprehensive database of the life cycle of all ground-related hazards. The status of a hazard can change if it is fully eliminated or if the risk changes due to interventions that reduce exposure, thereby mitigating potential consequences. For instance, installing a catch fence (an engineering barrier) or designing a step-out bench can effectively remove or protect personnel and equipment from the hazard, or in some cases it can be eliminated.

Step 7: Conduct verification inspections at set frequency

If the hazard status is active, the frequency of follow-up verification inspections is set, following a risk-based approach to ensure all controls remain in place and effective for all active hazards.

Benefits and Outcomes

The information system can instantly generate various reports from the real-time data, enhancing the efficiency of geotechnical engineers and strata control officers. The reporting format supports simple, effective communication and ensures timely management of hazards as they arise (Figure 8).



TARP Level Description

RANKING	PRIORITY	ACTION	DESCRIPTION
High	Stop & Fix	Controls are not in place and current control strategy will not function as intended	The situation must be rectified immediately. Stop work, implement interim controls, and implement controls to lower the risk
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Mitigated		Controls are in place; the control strategy is functioning as intended	No specific action is required, continue implementing the day-to-day standard operating procedures and controls

Hazard ID	Risk Level	Hazard Type	Tarp Level	Instructions	Additional Instructions
119(87 Area)	High	Multiple bench failure		Implement effective dewatering / depressurisation, Implement effective slope monitoring	
120(87 Area)	High	Multiple bench failure		Implement effective dewatering / depressurisation, Implement effective slope monitoring	
121(101 Area)	High	Overall Slope Failure		Implement effective dewatering / depressurisation, Implement effective slope monitoring	A butters berm has been constructed across the toe of the failing material to retain the material. This has resulted in a significant reduction in the rate of deformation of the failure.
126(Pushback 5)	Medium	Inter-ramp / stack failure		Implement effective dewatering / depressurisation, Implement effective slope monitoring	
127(Pushback 5)	Significant	Inter-ramp / stack failure		Implement effective dewatering / depressurisation, Implement effective surface water control, Implement effective slope monitoring	
134(GR80 west waste dump)					
125(PB5)	Significant	Rock fall	Low - Fix Within Schedule (Yellow)	Additional Instructions	Scale the highwall after loading and ensure the berm is constructed across the ramp
131(Pushback 4)	High	Rock fall (overspill)		Implement exclusion zones, Additional Instructions	Ensure that the dig line limit is loaded on Provision to prevent interaction of mining activities.
109(87 Area)	Significant	Multiple bench failure	Perform more rigorous design work required to improve reliability of the geotechnical design, ensure accurate mine to design, Implement effective surface water control, Implement effective slope monitoring, Implement operational controls		
111(Pushback 8)	Medium	Single bench failure	Low - Fix Within Schedule (Yellow)	Implement limit control, implement exclusion zones, Implement operational controls, Additional Instructions	This is a test
115(GR80)	Medium	Multiple bench failure		Implement exclusion zones, Implement operational controls	

Geotechnical Engineering	Technical Services Manager	Mining Operations	Survey	Safety	Mine Planning
SIGN:	SIGN:	SIGN:	SIGN:	SIGN:	SIGN:
DATE:	DATE:	DATE:	DATE:	DATE:	DATE:

Figure 8. An example of an auto-generated hazard map from the system (using test data for illustration purposes).

As discussed before, the fourth pillar of the risk management system focuses on learning from past FOG incidents to continuously improve safety. To facilitate this, a spatially-enabled database that captures detailed geotechnical data on FOG incidents was developed, allowing for in-depth analysis and identification of trends to enhance future safety strategies. (See Figure 9 for an example of the dashboard used to visualise this data and track progress). The following are captured for each FOG incident:

- Date / Time / Reported by
- Area name / Design sector
- Mining activity
- Incident type – single bench, rockfall etc.
- Failure mode
- Detailed description of incident
- Dimensions (volume)
- Run out / fall out distance
- Operations affected
- Evidence observed
- Explosives details
- Blasting practice
- Primary and secondary lithology
- Surface condition / structure / GSI / rock mass class
- Weathering
- Excessive rainfall recently recorded
- Seepage in face observed
- Extent of seepage
- Excessive ponding on the crest
- Incident classification-based safety and financial consequences
- Controlled / uncontrolled / significant / reportable.

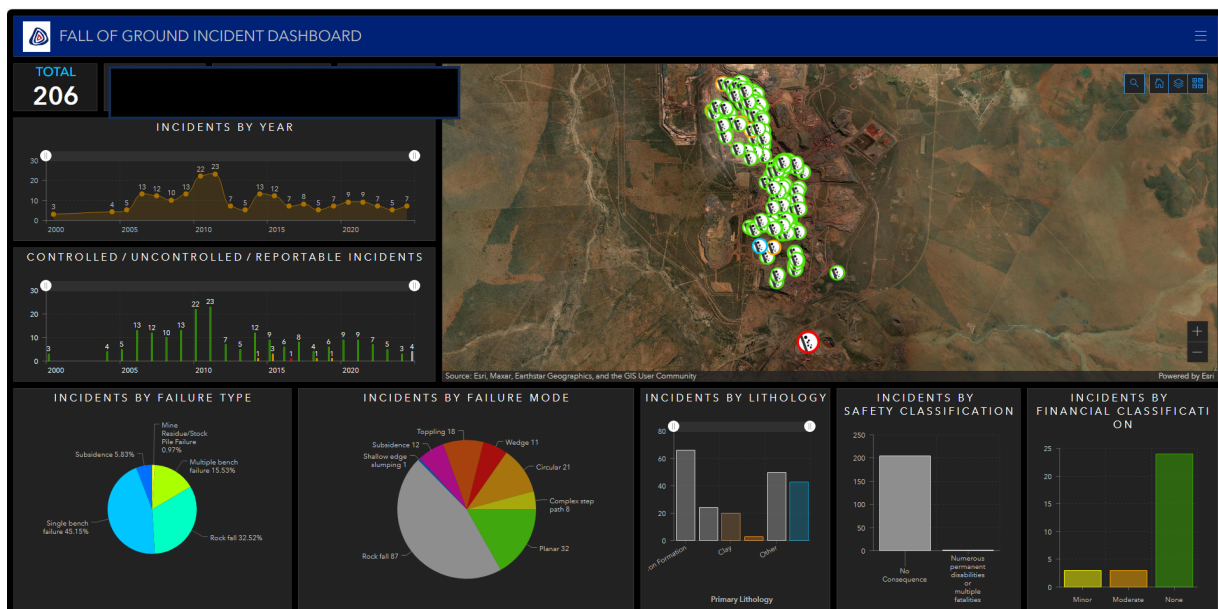


Figure 9. Example of fall of ground database with test data.

This system is further supported by a decision tree, aligned with the company FOG reporting framework, which classifies incidents based on criteria such as controlled, uncontrolled, significance, and reportability. This classification enables trend analysis to identify where controls may have failed.

DISCUSSION

Impact of Information Systems on Geotechnical Risk Management

The development of an information system that provides live hazard maps has significantly transformed and advanced the management of geotechnical risks, by enabling the tracking of the status of risk controls of all active FOG hazards in the operation, enabling improved decision-making and more effective geotechnical risk management. State-of-the-art drone technology and capturing all data in a spatially-enabled database enables the geotechnical engineer to provide clear instructions on what controls are required. Geotechnical engineers and mining operations can now track and assess hazards with greater precision, allowing for proactive risk mitigation. This system has streamlined workflows, enhanced collaboration between departments, and improved the accuracy of hazard maps, ultimately increasing safety and operational efficiency. Figure 10 shows an example of the live hazard map at Mogalakwena mine and a photo of a failure being managed operationally.



Figure 10. Example of live hazard map showing risk level and TARP level and zones of influence / no-go zones.

As the mining environment continues to evolve, the importance of continuous improvement in these systems cannot be overstated. The dynamic nature of mining and rock mass behaviour, coupled with technological advancements, necessitates regular updates and refinements to ensure that risk management practices remain relevant and effective. Continuous adaptation of information systems is crucial for maintaining the agility needed to respond to emerging threats and to maintain a culture of safety that evolves alongside the mining industry's needs.

Collaboration Across Disciplines

Collaboration between geotechnical engineers, systems engineers, surveyors, mine planning and production personnel is critical for addressing the complex challenges in mining operations. Managing FOG-related hazards are inherently interdisciplinary, requiring the expertise of various professionals to ensure safety and efficiency. Geotechnical engineers provide technical insights into soil and rock behaviour to timeously identify ground related hazards, subsequently working with operational personnel to design and implement the required controls to ensure safe delivery of the mine plan. They are supported by Survey, utilising various technologies to ensure precise spatial data is up-to-date and accessible. Automated information systems can then facilitate data management and decision-making

by converting raw data into actionable knowledge. By working together, these disciplines can develop comprehensive solutions that are both technically sound and operationally viable. The system enhances collaboration and communication by integrating a wide range of information sources, including hydrogeology, surface water management, waste dump risk, structural geology, geotechnical design risks related to safety and financial considerations, as well as monitoring data from INSAR for example (See Figure 11). This integration supports not only current operations but also future pushbacks.



Figure 11. Supplementary information can be made available for effective communication; for example, fault traces from the structural geological model, intersected with the current topography.

Collaboration fosters innovation and allows for more effective risk mitigation, improving overall mine safety and efficiency. Effective communication and real-time data sharing supports setting priorities and the right decisions. Tools like this therefore play a key role in facilitating this cross-disciplinary cooperation, ensuring that complex geotechnical challenges are addressed effectively and efficiently.

Future Directions

With the foundation of sound geotechnical information systems being implemented, the next frontier involves leveraging artificial intelligence (AI) to transform risk management processes. AI has the potential to automate and enhance decision-making by analysing large volumes of geotechnical data in real-time, identifying patterns, and predicting potential anomalies and/or deviations. Future research and development should focus on the integration of AI into existing information systems, enabling more accurate risk assessments and proactive hazard identification. Key areas for exploration include machine learning models that can predict FOG events, the development of intelligent geofencing systems that dynamically adjust based on real-time data, and AI-driven optimisation of mine design to mitigate geotechnical risks. Additionally, evolving best practices will likely focus on the use of AI to enhance risk assessments, and continuously improve operational safety. The integration of AI into geotechnical risk management will not only improve operational efficiency but also reduce risks, setting the stage for smarter, safer mining practices in the future.

CONCLUSION

In conclusion, leveraging real-time data and fostering effective communication through spatially enabled information systems has proven to be a vital step in identifying and effectively managing FOG hazards and associated risks promptly. This proactive approach enhances the efficiency of geotechnical engineers and strata control officers, enabling timely interventions that significantly mitigate FOG-related risks and contribute to a safer working environment. A key breakthrough of this contribution was the opportunity to improve the quality and effectiveness of hazard plans while establishing a

consistent process for identifying risks, assessing them, and effectively communicating control measures. The integration of technology and process-driven information management strategies sets a robust foundation for sustainable and effective geotechnical risk management.

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Marnus Bester

Principal Geotechnical Engineer
Anglo American

Marnus started his career in 2000 as a professional in training at the project, which is today the Kolomela Mine, after which he got appointed as a Geotechnical Engineer at Sishen Mine. In 2005 he relocated to Rosh Pinah Mine in Namibia to gain underground mining experience. Returning to Sishen Mine as Chief Geotechnical Engineer he has been involved in all geotechnical aspects relating to large open pit mining and mine dewatering as well as operations as a Production Manager. In 2012 he was appointed as Principal Geotechnical Engineer / Hydrogeology at Anglo American Kumba Iron Corporate Office with involvement in all operations and projects relating to Geotechnical Engineering and Hydrogeology. During this time, he completed his Ph.D. at Wits University under Prof Thomas Stacey. His thesis, A risk-based methodology to improve the definition of geotechnical design sectors in slope design, dealt with the optimisation of slope design through the application of Synthetic Rock Mass Modelling approaches and 3D modelling of the interaction of geological features with slope geometries. In 2020 he accepted a position at Anglo Corporate Office where his main responsibility is global mine waste dump and stockpile risk management for Anglo American as well as various other surface and underground projects.

Leveraging modern desktop computing power to enable full-fledged gravity terrain correction processing

P. Linzer

SRK Consulting, South Africa

Gravity surveying is a geophysical method for detecting subsurface density variations in mining and mining-related endeavours, such as mineral exploration, mine planning, and infrastructure siting. Such density variations can be produced by a variety of subsurface features, including orebodies, cavities, large water-bearing fissures, karst profiles, etc. Gravity surveys can also augment mining safety and risk management, e.g., as a tool for the early detection of incipient sinkholes in opencast operations. To be useful, the raw gravity field data require several reduction and processing steps, one of which is gravity terrain correction (GTC) processing. The latter step is often omitted owing mainly to its computational demand, thereby diminishing the value of the final survey data. This paper describes how recent advances in modern desktop computing technology with features such as hyper- and multithreading, multicore central processing units, instruction set extensions, and more, have made exhaustive GTC processing hugely more practicable. A resultant GTC processing code derived, prototyped, and developed in-house is briefly described. Finally, a synthetic example of a gravity survey conducted in a hypothetical open pit mine to detect subsurface cavities is presented, which illustrates the difference that proper GTC processing can make to a gravity survey's target delineation, definition, and contrast.

INTRODUCTION AND BACKGROUND

Problem outline

One among several geophysical techniques, the gravity survey is used for the detection of subsurface density anomalies, both high and low. It involves measuring the gravitational potential with a sensitive instrument called a *gravimeter* at a collection of points ('stations') on or near the Earth's surface, usually lying on a predefined grid, which forms part of a detailed gravity survey design that considers the survey's purpose and location.

The gravity method is useful in several mining and mining-related activities including mineral exploration, orebody and geological structure mapping, mine design and planning, infrastructure siting, mapping subsurface karst profiles, groundwater exploration, hydrogeological surveys, oil and gas exploration, and the detection of subsurface features such as cavities, large water-bearing fissures and aquifers. Some more obscure applications of the method include the mapping of old mine workings, and finding old bomb shelters, hidden tunnels, and pipes and sewers. These various applications identify the many potential causes that can produce subsurface density anomalies.

Gravity surveys can also assist with mining safety and risk management initiatives, for example as a method for the early detection of cavities that could become sinkholes in open pit ventures, since such events will endanger personnel and equipment, besides disrupting normal production operations.

However, the success and usefulness of a gravity survey's results depends critically on the correct application of the appropriate field discipline and protocols that will maximise the ultimate value of gravity survey data.

Gravity data corrections

Equally importantly, the raw gravity readings require processing to remove the effects of known phenomena that influence the data values before they can become fully meaningful. These corrections include:

- Gravimeter drift – temperature and instrument characteristics change slowly during use
- Latitude – Earth is spinning and is not perfectly spherical
- Elevation – a.k.a. free-air; distance to Earth's centre, per Newton's $g \propto 1/r^2$
- Bouguer – the mass between the reference and measurement elevations
- Earth tides – Moon's effect
- Regional – deep, large-scale, gradual variations that aren't of direct interest
- Eötvös – only for moving platforms; Earth's rotation and any east-west motion of the gravimeter
- Terrain – uneven topography, especially in the nearfield.

This paper focusses on the last of these, the terrain correction, and its importance.

Terrain effect on gravity measurements

The importance of the terrain correction cannot be overstated, especially in gravity surveys where the surrounding topography is highly variable (Blais and Ferland, 1984; LaFehr, 1991), and/or where anticipated density anomalies are small. In extreme cases, the nearby terrain's gravitational effect can cause an anomaly to be missed or written off as insignificant, or even to be completely masked. An example of an extreme case is a survey conducted in an open pit where the benches and highwall can mask gravity lows related to subsurface cavities.

Briefly, the terrain effect arises from two related mechanisms. The first of these is the case of a nearby hill or other elevated topographical feature, including manmade features such as a rock dump, which introduces excess mass that exerts a gravitational attraction on the measurement station. This attraction has a vertical component that acts upwards, thereby reducing the gravity reading at the station. The magnitude of this reduction depends on several factors, mainly the elevation difference between the station and the elevated terrain, the distance between them, and the average density of the elevated terrain portion.

The second mechanism is the case of a nearby valley or other topographical depression, including manmade features such as an open pit, which introduces a mass deficit that lies below the measurement station. The effect of this mass deficit is to reduce the downward gravitational force component exerted at the station, thereby reducing its gravity reading. The magnitude of the reduction depends mainly on the elevation difference between the station and the depressed terrain, and the distance between them.

Thus, the presence of both nearby hills and valleys tends to reduce gravity readings, and therefore the aggregated terrain correction for a measurement station will always be zero or greater and needs to be added to the uncorrected gravity readings. Moreover, it is worth noting that the terrain correction is entirely independent of all the other gravity data corrections mentioned earlier. (To be clear, while the terrain correction is apparently similar to the Bouguer correction, the latter considers only the elevation difference between the measurement station and the reference plane, not the effect of surrounding elevation variations).

Determining the terrain effect

The calculation of the terrain correction requires the positions and elevations of the measurement stations as well as a sampling of data for known points of the area containing and surrounding the gravity survey area. The latter component constitutes a terrain model that approximates the topographic features of the survey area and its surroundings. The terrain model's required point data

consist of positions, elevations, and local rock column densities if they are available (which typically they are not, and so a uniform density is usually assumed). The terrain model should extend a few tens of kilometres in all directions beyond the survey area. The preferred extent is largely dependent on the terrain's vertical variability—the more variable, the larger the terrain model extent should be—but rarely, if ever, does it exceed 160 km.

Early approaches to calculating terrain corrections, starting as far back as 1912, were developed by workers such as Bullard and Hayford (Connor and Connor, 2017), but a properly formalised method was only presented in 1939 by Hammer (Hammer, 1939). This method is still in occasional use today owing to its relative simplicity. The method uses a circular template that divides the area surrounding a measurement station into equal sectors and concentric rings to form a system of compartments called a 'Hammer net' (see Figure 1).

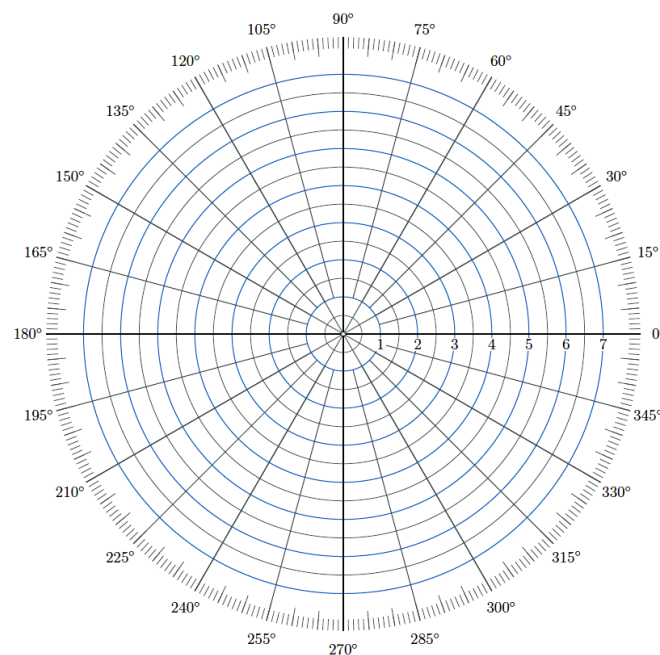


Figure 1. The Hammer net method template (adapted from Connor and Connor, 2017).

The Hammer net's centre is placed at the measurement station currently being considered on a topographic map, whereafter the average elevation in each compartment is calculated and used to determine the average elevation difference between the station and the compartment in question. Together with the inner and outer radii of the compartment, its angular extent, and a bulk density value of the terrain, a terrain correction value is calculated for the compartment. The total terrain correction for the station is then the sum of the corrections over all the compartments. Mathematically, it is a large numerical integral over the entire surrounding area for each station.

Hammer's method is obviously repetitive and laborious, and therefore prone to calculation errors if done manually – "Terrain corrections can be extremely tedious" (Milsom, 2003). For the same reason, the method lends itself well to computerisation. Some later methodological developments include fast Fourier transform computation of the terrain effect, the use of digital elevation models (DEMs), and model approaches that variously involve conic prisms, multiquadric equations, assumptions of uniformly sloping surfaces, and statistical assumptions regarding the areal distributions of elevations (Banerjee, 1998). These efforts have all sought to reduce the computational effort required to calculate the terrain effect reliably, and some of the later approaches can be classified as proxy methods because they avoid direct point-by-point calculation. The main shortcoming of all these proposed enhancements is that they tend to lose relevance precisely where accuracy is most critical, i.e., where the terrain varies wildly in the near vicinity of a gravity survey area.

The example Hammer net shown in Figure 1 has a total of 336 compartments. When using a DEM rather than a topographic map, each compartment can contain several elevation points, all of which need to be included in the calculations. Since a DEM is typically on a regular (near-)rectangular grid, the number of points in the compartments increases as their distance from the station at the centre of the net increases. Moreover, the calculations need to be done at every station, and a survey can consist of a few thousand stations, or even several hundred thousand for a large airborne survey. The number of point calculations is given by the product of the number of DEM points and the number of stations, which helps illustrate the formidable computational magnitude of the problem.

Modern desktop computing developments and their role

Several advances in desktop computing technology, principally hardware but also including software, can contribute significantly to alleviating the computation of terrain corrections. Among a few others, the hardware advances related to a modern personal computer's central processing unit (CPU) involve:

- Full 64-bit processing (providing faster primary operations, and the use and management of very large memory blocks)
- Instruction set extensions such as SSE n and AVX n that implement the SIMD concept (SIMD = Single Instruction, Multiple Data, allowing the same operation to be executed simultaneously on more than a single set of operands, e.g., pairwise multiplying together two equal-length lists of numbers; SSE n = Streaming SIMD Extensions version n , which provides some additional large CPU registers; and AVX n = Advanced Vector Extensions version n , which provides several further complex SIMD operations and up to 32 additional *very* large registers – up to 512 bits – for executing SIMD-type operations even more rapidly by avoiding external memory access penalties)
- Hyperthreading (within certain constraints, the CPU can execute two sequential instructions simultaneously in the same clock cycle), and
- Multicore processors for true parallel processing (a single CPU die can contain more than one physical processor, currently as many as 32).
(Liang, 2019)

Other hardware developments include larger and faster random-access memory (RAM) chips and more powerful graphics processing units (GPUs), which handle operations related to drawing and rendering of images on the computer screen. Modern GPUs are not passive in the sense that older-generation graphics cards were. The latter were fed final drawing instructions by the CPU after the CPU had processed data appropriately for the intended image. GPUs can accept unprocessed data and have their own data manipulation firmware for performing a range of raster and vector operations, thereby relieving the CPU of what could be significant computational burdens.

With regard to software improvements, pre-emptive multitasking operating systems (OSes) such as the Microsoft Windows NT family have benefitted from some of the aforementioned hardware developments, particularly in respect of using a CPU's multicore capabilities to implement true multitasking (in contrast to single-processor time-slice allocation and task-switching, both of which still occur, only on all available processors simultaneously) and providing the application programming interfaces required by user code for managing these facilities. Equally importantly, these OSes have seen some notable stability improvements over the recent past, increasing their robustness and native capabilities.

In addition, modern computers come equipped with unified extensible firmware interface (UEFI)-compliant basic hardware input-output firmware system via which the OS uses and manages connected or integrated hardware devices. A common feature in UEFI systems is the ability to virtualise each single *physical* processor into two (occasionally four) *logical* processors. That is, a 16-core processor can be made to look as though it had 32 processors available. This feature can be useful for running more than one virtual machine on a single system but introduces additional task-switching penalties. For high-intensity computing, CPU virtualisation should therefore be disabled.

Regarding GTC processing, these modern computing system features can be exploited by adapting the

problem to suit the available computing environment. Perhaps most obviously, the problem is eminently parallelisable because not only, as mentioned earlier, is each station's terrain correction calculation entirely independent of any of the other corrections (drift, latitude, etc.), each is also completely independent of any other station's terrain correction. This independence means that the calculations can be apportioned uniformly¹ to as many processors as are available, and even across multiple separate computer systems.

The gravity terrain correction code

Initial development and testing

During 2022 and 2023, a project commenced aimed at identifying subsurface cavities at the floor of an open pit mining excavation. A gravity survey was recommended and performed. The gravity data were properly reduced and processed, except for GTC processing. The final non-GTC survey data displayed clear artefacts produced by the nearby topography, specifically the benches, highwalls, and a large man-made structure. (Client confidentiality restrictions prevent the inclusion of further details and illustrative material concerning this case.)

The reason for omitting GTC processing initially was the unavailability of suitable software to perform this processing step. Although several codes are mentioned in the subject matter literature, in many cases they are no longer available, or they are outdated in terms of the platforms on which they will run, or they are too limited in terms of their capabilities and input data specifications, or all of these limitations together. And while some commercial packages and package extensions are currently available, their effectiveness is uncertain (apparently relying on simplifications and proxy approaches to improve speed, as described earlier), and their cost tends to be high.

These defects prompted considering the possibility of preparing an in-house GTC code. The principles of the Hammer net approach guided setting up a model of a survey station surrounded by a collection of vertical slabs where each DEM point represents a single slab. The required calculations were derived from first principles before being thoroughly examined for the purpose of eliminating any mathematical constructs that could result in computational inefficiencies if naively implemented. These optimisations included pre-calculating terms that would be repeated at a station for different terrain points being considered, the removal wherever possible of trigonometric functions in favour of Pythagorean ratios (the computation of trigonometric functions is *much* more time-consuming than square roots or straight ratios, typically by a whole order of magnitude or more), and replacing repeated divisions by constant factors or terms with multiplications by their inverses (division is computationally more expensive than multiplication).

These derivations and analyses revealed two tweaks that could be made to the adopted method to improve its accuracy, and they were duly included.

The refined algorithms were then implemented for rigorous testing in SAS², a powerful scripting environment for statistical and mathematical analyses. In addition to the measurement station positional data, a large DEM drawn from public-domain Shuttle Radar Topography Mission (SRTM) data, was used for testing. The DEM had a 1 arcsecond horizontal resolution (± 31 metres on the ground at the equator), while elevations were accurate to the nearest full metre. The SAS implementation was verified for correctness using an independent Microsoft Excel implementation (i.e., essentially a manual validation exercise) for several portions across a number of different measurement stations. Based on this testing, the SAS version was subsequently accepted as being correct and the standard for assessing any subsequent implementations.

¹ Uniform portion allotment comes with some challenges that will be discussed in more detail shortly.

² SAS = Statistical Analysis Software, see <https://www.sas.com>

The gravity survey data of the aforementioned project were then treated with the SAS GTC implementation and the terrain artefacts became noticeably less pronounced, allowing more reliable identification of subsurface anomalies. This first job also revealed the potential for a rare pathological case that was subsequently catered for in the code.

Standalone GTC code development

A later, much larger GTC task for a mineral exploration project arose, which showed the limitations of a scripting environment such as SAS in which code requires a purpose-built runtime environment that interprets and executes the scripted code. The runtime engine overhead slows down the execution rate significantly, requiring many CPU instructions to perform what appear to be even the simplest of scripted commands, even in runtime environments that execute precompiled intermediate code such as Python or Java.

This bottleneck necessitated the porting of the SAS code to a programming environment that would produce compiled native code that the CPU can execute directly without needing any intermediate support. Embarcadero Delphi RAD Studio v11.0 was used for this translation, which also enabled several other code enhancements and tweaks:

- No object-oriented programming constructs were used to avoid the additional processing overhead that these introduce.
- Multithreaded parallel processing was implemented in such a way that the code automatically deploys as many processing threads as there are logical CPUs (henceforth 'cores') available on the machine on which it is running, and each thread is assigned to a specific core to process a unique portion of the overall job, so as to make use of all available computing power. Each thread is in effect completely autonomous and produces its own output data file.
- The use of standard Delphi library code was extensively avoided in favour of direct Windows system calls (e.g., for file IO) and in several cases with homegrown replacement routines (e.g., trigonometric functions). The reason for doing this is that library code adds processing overhead, usually because it is generally applicable and caters for cases that simply do not occur in the code. For example, the standard trigonometric sine function, $\sin(x)$, makes provision for values of x that lie well outside of the normal $0 \leq x < 2\pi$ (radians) range, but the GTC code expressly prevents such out-of-range angles ever arising, so that the additional processing overhead is pointless and wasteful.
- A few frequently called primary functions were coded in x64 Assembly language to make greater use of the SIMD extensions after it became clear that the code compiler did automatic vectorisation only sparingly.
- A console program setup was used rather than a Windows GUI arrangement because writing user feedback in a console uses asynchronous buffered lazy writing instead of putting the writing program into a wait state until a GUI write operation has been completed, which can give a console process a slight performance advantage.
- The code allows a job to be parcelled out to multiple independent computers.
- The job configuration is defined in a simple text-based initialisation file.
- A running job can be halted at any time by a user and resumed later where it left off.
- The program's own and all its threads' execution priorities are set to the lowest rank to avoid the computer becoming unresponsive owing to high CPU load.

The approach of replacing library code with appropriate homegrown substitutions improved the GTC code's overall processing speed by 15 to 20%, compared to a benchmarking implementation that used only library code. The results were identical between the two versions.

It is therefore clear that the GTC program has a significant CPU demand, but it can also have a high RAM requirement. This aspect is determined by a combination of the number of stations, the number of DEM points, and the number of processing cores. The RAM is required for storing precalculated data. On startup, the GTC program will check for available physical RAM and emit a warning if it is insufficient but will commence processing regardless. The purpose of the warning is to alert the user because Windows will provide virtual RAM if physical RAM is insufficient, but this mechanism will

significantly impede processing rate.

GTC code input data requirements

Apart from the aforementioned job configuration file, the GTC code requires two separate input data files. Both of these files are expected in text-based CSV format. The first of these input files gives the survey stations' positional information, namely station locations in GPS coordinates and station elevations. The second input file similarly defines the DEM in terms of DEM point positions, but it also includes the rock column relative density for each DEM point. (Typically, these rock column densities are unknown, in which case a uniform representative value such as 2.5 is assumed.)

It should be clear that the DEM input data file is invariably much larger than the survey station definition file, containing many more points, including ones within the survey area itself. Indeed, the station positions themselves are included in the DEM data.

The DEM itself can be constituted from several different DEM or DTM sources (e.g., SRTM and any in-house client terrain elevation data) but it is critically important that they are all corrected to the same elevation datum before they are amalgamated.

In all cases where the GTC code was applied up to the present, it was found that the elevation datums differed between the DEM and the survey area. The reasons for this difference in datums include different surveying techniques, topographical changes over time, and different reference datums. Obviously, an appropriate reconciliation between the different datums was needed to avoid erroneous GTC results, and this problem was at first addressed via a separate SAS script but later coded into a separate GTC support program owing to the problem's ubiquity and the relative slowness of the SAS script for performing the datum reconciliation.

Additional GTC support codes

The datum problem was addressed using an inverse-distance weighted scheme that considers the three horizontally nearest DEM points to each station to calculate a datum correction. A single overall datum shift is then calculated from the individual stations' corrections using the inverse of the distance to the nearest DEM point as a weighting factor. This final datum correction is then applied to each station elevation. As mentioned, this scheme was implemented as a separate GTC support code, in this case a required preprocessing step.

Four other support codes were found to be necessary to address tangential GTC processing issues:

- A SAS script for importing raw gravity survey and DEM datasets, incorporating station data in the DEM, trimming the DEM to a circular area of sufficient size (default is 100 km in all directions beyond the survey area), and exporting them in the correct CSV format, as required by the GTC code. The script includes simple plotting features that allow the user to verify geographical correctness of the survey and DEM areas, and to examine the relationship between their datums
- A separate standalone code that calculates for each survey station a series of geometrical statistics for all DEM points that lie within a user-defined distance of the station, say 100 m. This utility is useful for identifying stations at which GTC calculations are potentially problematic, for example where a DEM point lies very close to a station but the two have significantly different elevations
- A crash recovery program. It has happened occasionally that high-spec computers shut down suddenly because of CPU overheating (a.k.a., thermal events) from sustained near-100% load. The recovery program trims trailing partial writes from the output data files and corrects / updates the job configuration file so that GTC processing can later be resumed with each thread starting from the last properly completed station
- An assistant application for deploying a job on more than one computer. This program accepts a list of target computers together with certain technical specifications of each one (CPU type, clock speed, cores, installed RAM) and assigns the processing in such a way that the expected completion times for all machines are all equal.

There was also an earlier additional support code the functionality of which was subsequently added to the GTC code itself. This functionality automatically reassigns the processing threads to different cores, depending on their processing rates, with the aim of all threads completing more or less simultaneously to minimise total processing time. The main reasons for including this feature are (i) the major CPU manufacturers (chiefly, Intel and AMD) have a mix of so-called ‘performance’ and ‘efficiency’ cores on their CPUs, which core types intrinsically process at different rates; (ii) other concurrent processes often place intermittently high loads on a few selected cores, and (iii) Microsoft Windows CPU load balancing is often suboptimal with different cores being assigned disparate loads.

The GTC program in action

Program appearance and status reporting

Figure 2 shows the GTC program while running. As described earlier, the user interface is in the form of a console. While rudimentary, it provides information in the form of an optional job name, the statuses of input data file reads, the size and station count of the survey, and the size and point count of the DEM. The term ‘radius’ is used to describe the smallest circle that contains all of the survey stations and should not be read as implying that the survey itself covers a circular area. In contrast, the DEM area is indeed circular, having been trimmed thus by the preprocessing SAS script.

In addition to the job parameters, the console also displays per-thread progress, the time it has been active, and its overall progress. In the example shown, five of the 12 threads have completed their respective portions of the job. Some system menu, title bar, and keyboard shortcut controls of the console have been disabled to avoid inadvertent closing of the program, and the user is required to use the standard console **<Ctrl>+<C>** keystroke combination to terminate a processing session gracefully. On termination, the program reassigns the threads according to their individual rates (slowest to fastest and vice versa) and displays the overall processing rate for the session in terms of the number of stations completed per minute.

Finally, any errors that may occur – for example, an invalid job specification file or faulty input data files – are reported on the console as they are encountered. Any error terminates the job, but the console will remain open until the user acknowledges it.

```

DO NOT CLOSE: Processing critical gravity terrain corrections
Job name: Synthetic in-pit test, 2024
Reading survey data 0.050 sec OKAY
Reading DEM data 3.241 sec OKAY
Survey: 31,341 stations, radius = 99.990 m
DEM: 3,384,209 points, radius = 100.459 km
OKAY : Thread 1 started at station 19,417 Processing 1236 of 1481
OKAY : Thread 2 started at station 29,861 Processing 1359 of 1481
OKAY : Thread 3 started at station 24,605 Processing 1481 of 1517
OKAY : Thread 4 started at station 14,120 Processing 1517 of 1554
OKAY : Thread 5 started at station 16,788 Processing 1465 of 1498
OKAY : Thread 6 started at station 8,901 Stopped at station 10,450.
OKAY : Thread 7 started at station 11,455 Stopped at station 13,062.
OKAY : Thread 8 started at station 777 Processing 1675 of 1817
OKAY : Thread 9 started at station 27,247 Stopped at station 28,734.
OKAY : Thread 10 started at station 6,240 Stopped at station 7,838.
OKAY : Thread 11 started at station 21,894 Stopped at station 23,510.
OKAY : Thread 12 started at station 3,516 Processing 1634 of 1710
Time used terrain-correcting gravity data: 2:14:43 (18216 stations)

```

Figure 2. The GTC code running on a 12-core laptop (Intel 2.2 GHz i7 CPU + 48 GB RAM).

A real-world example of GTC processing

Figure 3 shows an excerpt of the same area from two final gravity data plots of a large airborne gravity survey done on a regular grid point spacing of about 25 m. All the required gravity data corrections

were performed in both cases, except for GTC processing, which was omitted from the plot on the left. It is worth noting that in many cases, the plot on the left is considered the final output of a gravity survey because the terrain correction, being problematic, is often omitted for reasons stated earlier.

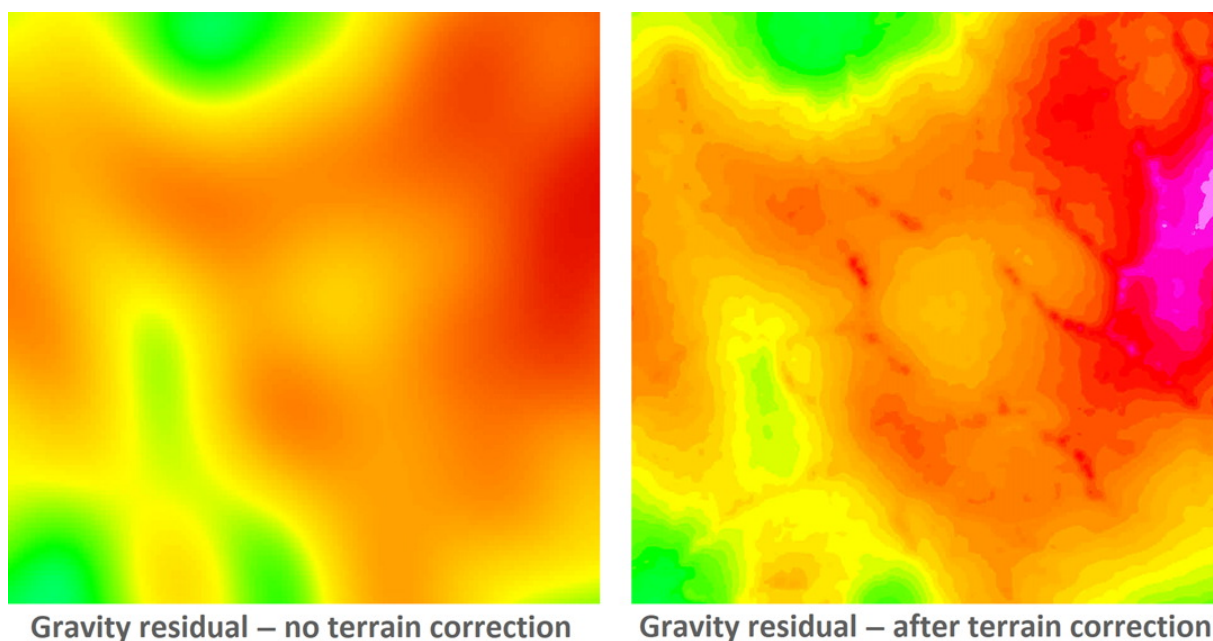


Figure 3. Areal gravity residual plots of the same area. GTC processing was omitted from the plot on the left.

The differences between the plots are immediately clear. In this case, GTC processing has significantly enhanced gravity residual definition, contrast, and resolution with intensity contours being more unambiguously demarcated. The terrain surrounding this survey is mountainous with nearby elevation variations of a few hundred metres, and their combined effect appears to have smeared out the areal gravity variations.

It was noted that some of the GTC-enhanced gravity features seem to echo the terrain's local topography, and many features identified by this survey correlated well with the results of a simultaneous aeromagnetic survey. However, a detailed analysis and interpretation of the results lies outside of this author's area of expertise and is not this paper's primary focus.

A synthetic example of GTC processing

As a further illustration of the value that proper GTC processing can add to a gravity survey, a synthetic example was created of a hypothetical open pit mine at the floor of which subsurface cavities are sought using a gravity survey.

The pit is assumed to have a circular footprint with five benches and a spherical subsurface cavity located halfway between the pit floor centre and its periphery. Figure 4 shows a vertical section through the pit's centre with its salient dimensions.

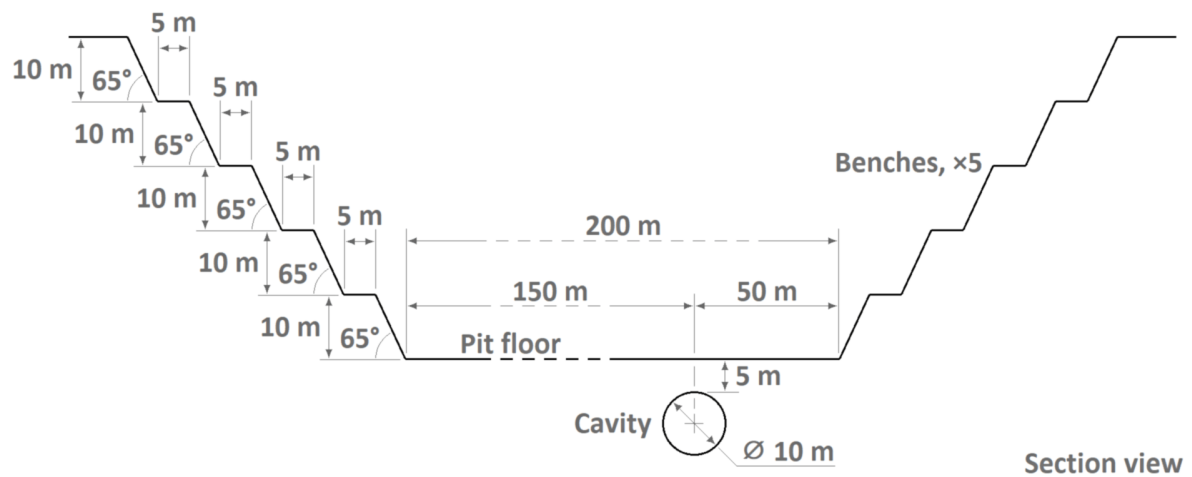


Figure 4. Section view showing the geometry and dimensions of a hypothetical circular opencast pit with a shallow spherical subsurface cavity off to one side.

The surface terrain surrounding the pit is assumed to be sufficiently flat and even in all directions, and its effect is therefore omitted from the GTC processing. Thus, only the effect of the benches on gravity at the pit's floor is considered in this example.

Figure 5 shows the difference between the non-GTC and the GTC processed data when plotted. The non-GTC processed data (plot on the left in the figure) shows a systematic increase in gravity values from the pit floor's edge towards its centre. This effect is wholly attributable to the presence of the benches which lie above the measurement elevation. The benches exert a net upward gravitational force at the measurement stations which force decreases as the distance from the benches increases, explaining lower gravity values at the pit floor periphery compared to its centre.

As can be seen, once the effect of the benches has been removed by GTC processing, the presence of the cavity is brought into much starker relief (plot on the right in the figure).

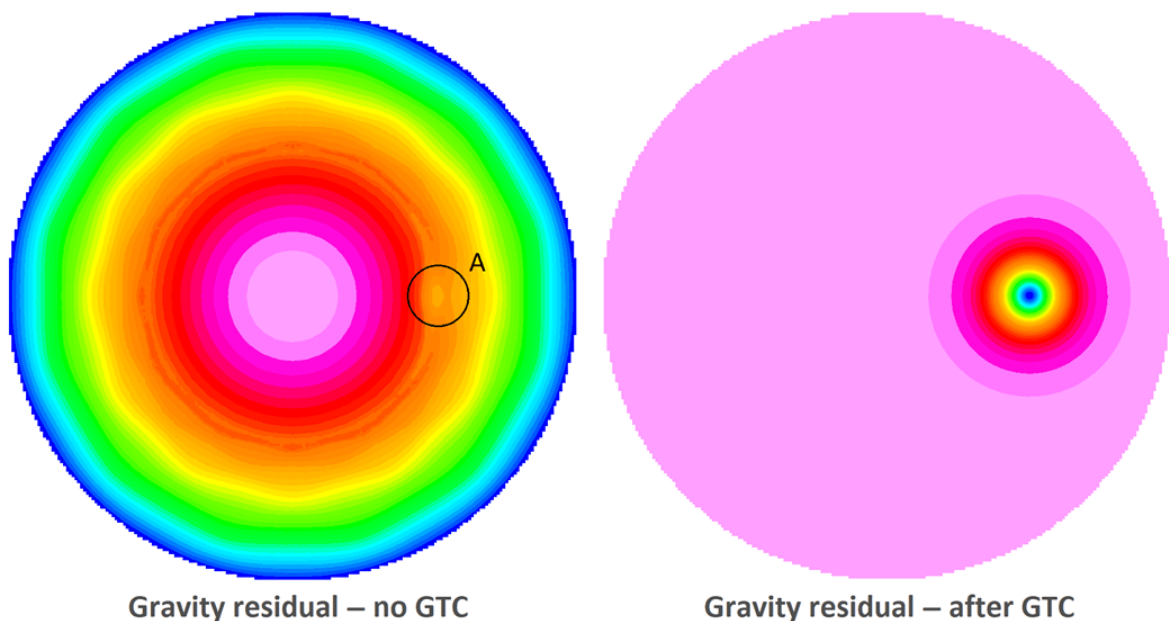


Figure 5. Gravity residual plots at the pit floor for the synthetic example with and without GTC processing.

The non-GTC plot also identifies a small anomaly labelled 'A' that resulted from the cavity. The anomaly is very small in magnitude relative to its immediate surroundings, and it could therefore easily be written off as insignificant or even missed entirely. It should be noted that the terrain's effect can mask faint signals that may be of critical importance. If, in a similar real-world scenario the presence of the cavity was missed due to it being masked by the benches and it were subsequently to collapse, the mine operator might rightly question the usefulness of doing gravity surveys as a safety precaution against such an eventuality.

CONCLUSIONS AND RECOMMENDATIONS

By way of both a real-world and a synthetic example, the present work has demonstrated the value that full-fledged GTC processing can add to gravity surveys. The in-house code development for this purpose was described in some detail and with reference to several modern desktop computing system features that were exploited to enhance the code's efficiency, given that it is a computationally highly demanding task.

The benefits provided by GTC processing include improved target detection and isolation, and clearer resolution of subsurface density variations. GTC processing becomes increasingly important where anticipated targets are faint and/or where the surrounding terrain is highly variable, especially in the nearfield region. These benefits can assist with or improve project execution in a variety of ways across several disciplines, including mining, civil engineering, geological, exploration, and geotechnical work. Wherever a gravity survey is desired or indicated, GTC processing can be advantageous.

However, a useful rule/guideline/formula/heuristic is still needed to assist with deciding whether proper GTC processing is justified in a given gravity survey scenario. For now, it is recommended that it be done for every survey since doing so will provide the necessary empirical data to establish the missing decision rule(s).

Besides the need for these decision principles, techniques for progressively coarser-grained re-gridding of the DEM with distance from its centre should be examined, owing to the significant reduction in computational effort it could entail.

Finally, where reprocessing of historical gravity data to include GTC is being contemplated, it should be borne in mind that the surrounding terrain may have changed, perhaps significantly so in the immediate vicinity (such as in the case of an open pit mine), from the time when the survey was done, and therefore current DEMs may no longer be sufficiently accurate to facilitate meaningful improvements. In this regard, gravity practitioners should not neglect the terrain's time dependency.

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Multi-purposing of passive seismic acquisition for characterisation and monitoring of tailings dam performance

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Passive seismic methods have been gaining momentum in the last two decades as geophysical tools allowing for both characterisation and monitoring of the subsurface physical properties in an innovative, cost-effective and non-invasive way. Their relevance for the surveillance of geotechnical objects such as earth levees, tailing dams, or open-pit slopes has also been increasing, particularly thanks to the unique monitoring capabilities of the methods. Continuous, passive measurements of ambient seismic noise can primarily be used to track microseismic events, analyse their origin and study the response of the monitored geotechnical structure. Here we illustrate how passive recordings of ambient seismic noise can be multi-purposed to provide enhanced monitoring and characterisation capabilities and increase the level of understanding and performance of geotechnical structures.

Ambient noise seismic interferometry is a passive seismic approach that provides a way to monitor continuously the shear wave velocity (V_s) variations occurring within geotechnical structures, with a 3D volumetric sensitivity, relying solely on the recording of ambient seismic noise. Physics links V_s changes to the dynamics of geotechnical parameters such as pore pressure and vertical stress, which are critical in tailing dams or open-pit slopes management strategies. Applied to tailing dams, this technology opens the way to a volumetric monitoring tool able to detect and report on anomalous evolution of geotechnical parameters such as pore pressure and compaction degree within the structure, at the foundation level and below the tailing dam itself. In addition to the surveillance of relative V_s changes, the same data set can also be used to derive a 3D model of absolute V_s values, revealing the internal structure of the dam wall. The multi-purpose potential of passive seismic recordings also extends to the derivation of key geotechnical parameters such as fundamental resonance frequency (through horizontal to vertical spectral ratio analysis), or damping ratio evaluation (through the random decrement technique).

This set of passive seismic methodologies is at the heart of an integrated technical solution which can provide the mining industry actors with the capacity to characterise the 3D structure of their assets, study their response to seismic excitations, and monitor their internal evolution. This solution encompasses a fully autonomous acquisition system, coupled with the Internet of Things equipment that allows for real-time data transfer to a data processing centre, where automatic routines provide quasi-real time monitoring of the internal evolution of the dam wall and other geotechnical parameters. Results can be delivered through a dedicated platform or integrated into the client's own monitoring dashboard. The objective of this integrated solution is to provide the mining industry with the capacity to enhance their monitoring capacity of geotechnical assets. The multiplicity of information (microseismicity, damping parameters, resonance behaviour, V_s models and evolution), powered by unique technical capacities (automation, continuity in time, non-invasive and volumetric assessment) and coupled with a client-oriented design (interoperability, security, auditability) provides new geophysical insights to complement and strengthen the strategies deployed for tailing dams management and performance monitoring.

INTRODUCTION

Continuous monitoring of geotechnical assets such as tailing dams, earth levees or open-pit slopes is crucial for early detection of potential instabilities, helping to prevent critical failures that could lead to significant environmental and human disasters. Additionally, continuous monitoring enhances our understanding of the complex interactions between the dam structure, underlying geology, and external factors like water infiltration, contributing to better understanding of the risks enabling safer and more effective dam management practices. A surveillance strategy and monitoring plan for those geotechnical assets generally relies on geotechnical, hydrogeological and geophysical measurements. Onsite investigations comprising in-situ geotechnical techniques such as cone penetration tests (CPTu) provide direct measurements of various physical parameters, allowing for better direct assessment of the geotechnical characteristics (e.g., Robertson, 2010; Torres Cruz, 2016). Other instruments such as vibrating wire piezometers (VWP) or inclinometers can be installed in-situ across a facility to provide information (displacement and pore pressure, respectively) continuously in time (Illanes *et al.*, 2015 ; Clarkson *et al.*, 2021). These types of digital monitoring techniques and solutions provide accurate in-situ measurements and high temporal resolution sampling, but the spatial extension of information is limited to quasi-punctual locations. Satellite interferometric synthetic aperture radar or ground-based radar surveillance methods support the monitoring of surface displacements across a wider extent, but information is limited by providing an evaluation of surface movements (Thomas *et al.*, 2019). This is also true for aerial drone surveys.

Geophysical methods are often used to fill in the lack of spatially distributed information for they have the capacity to infer subsurface properties in a volumetric way to provide models of the geotechnical target geophysical properties continuously with both depth and lateral extension, in a non-invasive way. Among them, electrical resistivity tomography methods are sensitive to moisture content, saturation levels and porosity values hence allowing to image the distribution of material types and reflect hydrogeological behaviors within the targeted structures (e.g., Oliveira *et al.*, 2024). Seismic methods are also used to derive models of seismic properties. Seismic refraction methods use compression wave analysis to detect significant vertical interfaces within the structure, delineating material types and /or bedrock depth for instance (e.g., Guedes *et al.*, 2023). Multi-channel analysis of surface waves is another active seismic technique allowing to derive shear-wave velocity (Vs) models of the targets; a relevant parameter to assess the stiffness and strength characteristics of the geotechnical structure (e.g., Prodosimi *et al.*, 2021). The main limitation with such active geophysical surveys is that they are difficult to repeat regularly in time for logistics reasons (repeated access to a dam, with repeated installation of technical devices) and high ongoing costs and are therefore not well-suited to performance monitoring with high temporal resolution.

In summary, accurate, continuous monitoring of a structure's geotechnical parameters is generally achieved by means of in-situ measurements, which are disadvantaged by limited distribution in space. As such monitoring and surveillance strategies are more readily deploying geophysical methods to investigate an asset's internal structure with depth and lateral extension, they rely on volumetric, non-invasive measurements. In this paper, we present how passive seismic methods can be multi-purposed to enhance both the characterisation and the performance monitoring aspects of a tailings dam surveillance, closing the gap between dynamic geotechnical and static geophysical measurements. The same data can be processed in different ways to provide multiple types of geotechnical and geophysical parameters, with both lateral and deep spatial distribution as well as continuity over time. In addition, the passive seismic monitoring method has the potential to deliver earlier indications of developing weakness in the structure, permitting sufficient time for the responsible engineers and asset owners to intervene to mitigate the risk of failure or damage.

Passive seismic methods rely on the recording of the ambient seismic signal using autonomous or semi-autonomous seismic sensors with long-term data storage or wireless data transmission capabilities. The information contained in the ambient seismic noise signal is rich, and various analysis methods can be deployed to extract this information. A powerful, innovative approach consists of using ambient noise seismic interferometry (ANSI) to extract coherent shear waves from the ambient noise, analysing the

reconstructed wavefield to infer V_s values (Shapiro & Campillo, 2004; Mordret *et al.*, 2020). V_s is a particularly relevant geophysical parameter in tailings dam or open-pit slope management because it is primarily controlled by pore pressure and vertical stress (Fokker *et al.*, 2021), two critical parameters that control the soil's mechanical behaviour and hence the stability of dams and slopes. One major strength of ANSI is its capacity to provide information quasi-continuously in time, for V_s values can be inferred sequentially at multiple time-steps (usually hours or days depending on the ambient noise characteristics) during the period of the ambient seismic signal recording (Mordret *et al.*, 2020). In addition to continuity, in this paper we illustrate in the context of tailings dam monitoring how V_s variations can be determined and visualised in 3D space, hence revealing differential lateral and depth behaviours, providing indirect estimation of hydrogeological parameters (pore pressure, phreatic surface level variations) and geomechanical evolution, offering combined spatial and temporal insight within the geotechnical structure that no other method commonly used in tailing dams surveillance can achieve.

Another approach that can be derived from the same passive seismic data is more commonly known as microseismic analysis. By analysing the seismic signals generated by microseismic events or blasts and changes in the dam's structure, operators can assess the integrity of the dam in real-time, monitor continued changes or implement timely mitigation measures. Beyond microseismic analysis, passive seismic recordings can also provide valuable parameters such as resonance frequency and damping ratio. These parameters characterise the dam's resonance behaviour and its response to seismic event solicitations, such as blasting and earth tremors. Fundamental resonant frequency values can be extracted from ambient seismic noise using horizontal to vertical spectral ratio (HVSr) techniques. They indicate a specific seismic frequency range for which the soil layers overlying the bedrock enters in a resonance behaviour when submitted to seismic excitation. These methods are widely used in geotechnical studies within urban environments to assess the seismic response of sedimentary layers and/or structures (Bonnefoy-Claudet *et al.*, 2006a, b). In this paper, we demonstrate how single-sensor measurements at the surface can reveal the thickness and seismic velocity distribution of the resonant part of the dam at any given location. Furthermore, multiple measurements across various locations provide insights into the lateral variations of the dam's resonant layer, shedding light on its internal structural heterogeneities. In addition to resonance frequency, damping ratio values are often used within geomechanical modelling processes to simulate and anticipate the geotechnical asset resistance to seismic excitation. They indicate how fast seismic energy will dissipate during a seismic event propagation within a structure. Such values are often extracted from literature, and potentially from laboratory measurements. In this paper we illustrate how damping ratio values integrated over the entire soil column can be derived from ambient seismic noise recordings, providing in-field evaluation of this critical parameter.

The subsurface geotechnical and hydrogeological parameters are difficult to monitor continuously both in time and space. We present in this paper an integrated solution based on passive seismic recordings which offers an effective way to respond to both challenges, using a single passive seismic dataset, to provide volumetric assessment and quasi-continuous monitoring of the tailings dam, with reduced maintenance and on-site logistics compared to active geophysics or invasive in-situ measurements.

PASSIVE SEISMIC ACQUISITION

Recording the ambient seismic signal is done through the deployment of seismic sensor stations. Such stations can have different configurations depending on the geotechnical monitoring or characterisation objectives. For a temporary analysis (a few weeks or months duration), as would be required for a feasibility study, 1-component (1C) or 3-component (3C) geophones can be seismically well coupled with the target structure through burial in holes to tens of centimetres depth, and associated with semi-autonomous acquisition units, or seismic recorders (e.g., 1b), which require regular replacement on a weekly or monthly basis to retrieve the data and recharge the internal batteries. For permanent monitoring and characterisation, fully autonomous stations can be installed (e.g., 1c), which are equipped with the Internet of Things equipment and allow for real-time data transfer to the data

processing centre where Vs analysis is performed. 1a) illustrates the seismic sensor network that was installed at the surface of a tailings dam for a period of eight months, with some stations in place for only three months. Continuous 3-component ambient seismic noise records were acquired at a sampling rate of 250 Hz, using geophones with a cut-off frequency of 4.5 Hz. Note that such an instrumental response allows retrieval of seismic signal at frequencies as low as 0.5 Hz (e.g. Kremer *et al.*, 2023).

In the following sections, we present a multi-purpose processing sequence applied to this passive seismic dataset which provides multiple outputs and insights into the tailings dam structure, composition and geotechnical evolution. This single geophysical dataset delivers a set of tools and metrics that have the potential to significantly enhance the current performance monitoring and geotechnical characterisation capabilities of engineers. The passive seismic approach provides a non-invasive, continuous, near real-time volumetric assessment of the structure that both complements, and cross-validates point measurements usually made by geotechnical engineers.

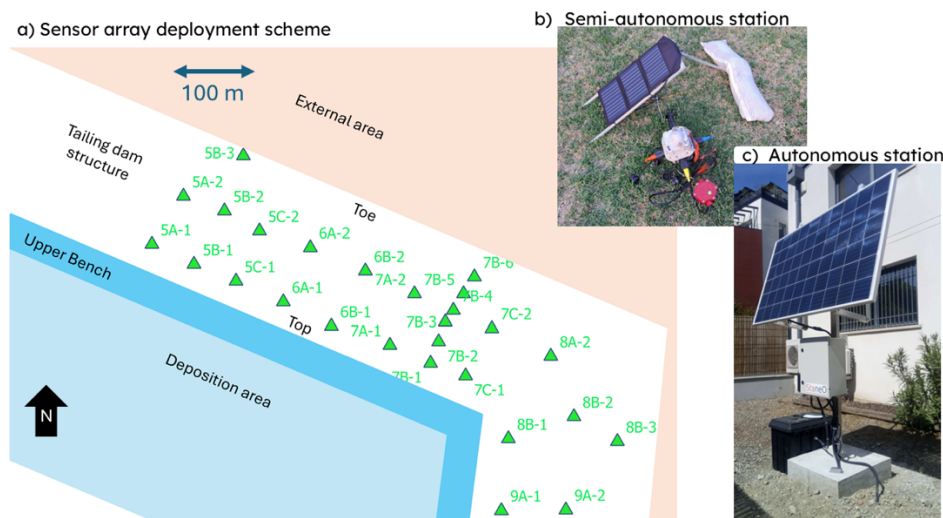


Figure 1. a) Illustrative scheme of seismic sensors deployment on a tailings dam. 27 semi-autonomous stations have been deployed for eight and three months to record passive seismic signals.

MONITORING - 4D SHEAR WAVE VELOCITY ANALYSIS

Methods

The internal physical properties of geotechnical assets such as tailing dams and earth levees are often challenging to characterise and monitor. In-situ instruments and measurements are accurate but only provide local information and are based on invasive methods. In this paragraph we illustrate in the context of a tailings dam monitoring use-case how passive seismic recordings can be processed to obtain Vs evolution time-series through the whole dam volume. Imaging techniques then provide ways to obtain temporal information in depth and with a large lateral coverage, complementing the lack of information between local investigation data (e.g., CPTu or seismic(s)CPTu), and in-situ instrumentation measurements (VWP and inclinometers).

The ambient seismic signal recorded over a network of seismic sensors can be processed by means of ambient-noise seismic interferometry (ANSI) methods to extract a coherent seismic wavefield (Wapenaar *et al.*, 2010a). Such wavefield is composed of coherent seismic arrivals both in the ballistic part (early arrivals) and in the coda part (late arrivals resulting from multiple wave diffusion processes). The wavefield is generally dominated by surface waves, making it possible to retrieve Vs relative variations by analysing how the time arrival of coherent phases changes with time, using for instance the so-called stretching method (Sens-Schönfelder and Wegler, 2006). In the context of tailings dam surveillance, the seismic noise components used for analysis are associated to relatively high frequencies (> 1 Hz) to accommodate the depth sensitivity of surface wave to the geotechnical target

decametric scale. At those frequencies, the seismic noise is mostly composed of signals with anthropogenic origin, which usually confer some instability on the wavefield reconstruction process (Afonin *et al.*, 2022) due to variations in the noise source distribution (e.g. night vs day, working days vs weekends). To reduce the effect of noise source instability and the resulting uncertainty in Vs variations measurements, we chose in the following analysis to focus on the coda part of the reconstructed signals (Wang *et al.*, 2008). To summarise, in the following, all Vs variations time-series were computed analysing time-shifts within the reconstructed coda wavefield, by means of the stretching method. A satisfying uncertainty level was obtained by deriving such measurements every 48 hours, taking advantage of signal-to-noise enhancement related to stacking processes.

Figure 2 illustrates the depth and lateral sensitivity distributions associated with the analysis of coda waves reconstructed through ANSI processes applied to single stations measurements. Figure 2a) shows an example of the 2D lateral sensitivity distribution computed for a synthetic array of 36 sensors deployed regularly in space. The resulting distribution is globally homogeneous with an increase of sensitivity in the centre of the array. Figure 2b) illustrates how the sensitivity in depth is dependent on the frequency range chosen for seismic data analysis. In the following, both types of sensitivity distributions are used and combined within inversion and imaging processes to provide the spatial and temporal visualisation required for tailings dam volumetric monitoring of Vs variations within the tailings dam.

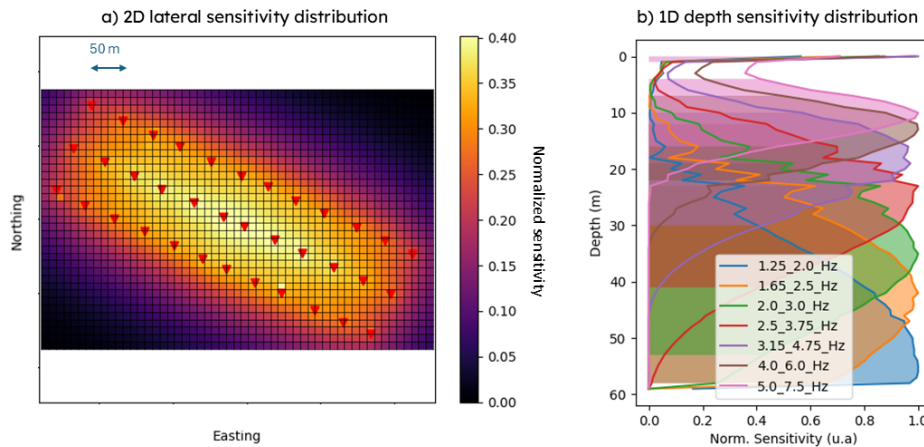


Figure 2. a) 2D lateral sensitivity distribution associated with Vs measurements on coda waves reconstructed through interferometry. Illustration for a synthetic regular array. b) Depth sensitivity distribution depending on the frequency content of the seismic wavefield. Filled area under the curve corresponds to 80% sensitivity for each frequency range.

Sensitivity to geotechnical and hydrogeological parameters

Figure 3 illustrates how Vs variations are correlated with various types of geotechnical, hydrogeological parameters and surveillance data, illustrating how passive seismic monitoring informs on the physical processes occurring within the tailings dam. The multi-coloured curves on Figure 3 represent Vs variations measured at some locations of the tailings dam, with distance in between stations ranging from 50 to 100 m (cf. Figure 1). They represent Vs evolution for a frequency range associated with a depth sensitivity ranging from 20 to 50 m (Figure 3b). All curves show similar behaviours, indicating that with this small spatial extent (~100 m) the tailings dam internal evolution at those depth is rather homogeneous. Error bars are not represented for readability, but indicate that the resolution of Vs change measurements (dv or dv/v) is on the order of 0.2%

Figure 3 highlights how internal Vs changes are primarily representative of the hydrogeological evolution of the medium. A clear anti-correlation can be observed relating the phreatic level time series and Vs evolution, confirming that Vs is primarily sensitive to pore pressure evolution; in that case induced by phreatic surface level variation. The elevation of the phreatic level does indeed induce a

small pore pressure variation that affects the whole water column within the tailings dam wall, thereby inducing a change in Vs affecting the saturated tailings layer. Assessing quantitatively, this relationship (through a linear correlation for instance) and considering the resolution of Vs variations measurements previously cited ($\sim 0.2\%$) implies that in the present case, the observed Vs changes reflect relative phreatic level changes on a centimetric order.

Another insight from Figure 3 is the effect of precipitation events on the internal composition of the dam, which shows on the Vs change time-series. In particular, a strong drop of Vs is observed after the first significant rain events that occurred at the beginning of November 2024. Sudden Vs decrease can be interpreted as an increase in pore pressure associated with infiltration of the meteoric water within the tailings dam formations. Other rainfalls with similar daily magnitude occur in the following weeks, but do not result in such a strong decrease of Vs. One explanation of this difference can be found in the dynamics of those rain events, as illustrated within the dashed-line rectangles. It is likely that strong, intense rainfalls result in a lot of surface run-off and little infiltration within the tailings material, whereas slow, continuous rainfall favours such infiltration and the associated modification of the dam seismic properties. Those observations illustrate how passive seismic Vs monitoring can be used to assess the effects of meteorological events on geotechnical structure composition; a tool that will be increasingly necessary in the upcoming changing climate – which is expected to produce an increased number of events with high intensity.

Another indication of Vs relationship with the evolution of the tailings dam can be found while observing cyclic behaviours of Vs evolution that may relate to deposition patterns, i.e., modification of the dam structure following the deposition of new amounts of tailings material. Such cyclicity is highlighted in Figure 3 by the black rectangle and double arrows. It shows as relatively fast decrease of Vs, which could be associated with infiltration of deposition water within the dam layers, followed by a slower increase of Vs that suggests desaturation or decrease of the phreatic surface level, possibly associated with progressive compaction processes.

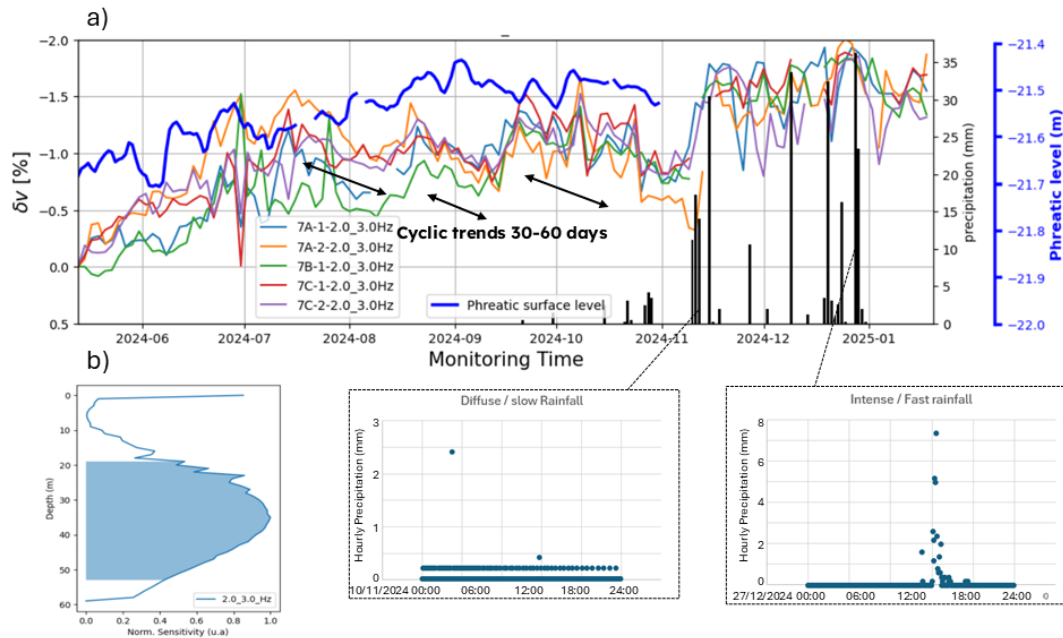


Figure 3. a) Vs variations curves (δv , multi-colours curves) in comparison with various types of data. Black histogram reports precipitation history. The thick blue curve reports phreatic level estimation derived from VWP data installed at the same location on the dam (data missing after 11/2024). The black rectangle highlights cyclic trends possibly linked to deposition patterns. Dashed-line rectangles emphasise the different dynamics of two rainfall events. b) Depth sensitivity distribution for frequency range [2.0 Hz -3.0 Hz].

Evolutionary 2D Vs maps

A more advanced interpretation of Vs variations time-series with respect to their localisation in space can be achieved using imaging techniques such as interpolation and inversion processes. Figure 4 shows an example of how 2D Vs maps can be produced at multiple times during the monitoring period, for different frequency ranges and hence depth sensitivity. Figure 4a) and 4b) illustrate that, within the shallow part of the dam, the Vs variations spatial distribution with respect to a reference date (19/11/2024) has been rather homogeneous in space, remained quite low at the beginning of the period (29/11/2024, Figure 4a) and showed a significant increase several days later (23/12/2024). Figure 4b), suggesting pore pressure decrease associated with desaturation and/or compaction effects. Figure 4c) and 4d) illustrate that for the same period of time, at deeper locations within the tailing dam, the Vs variations have been slightly increasing at first, and then a differential behaviour is observed between the western part of the dam where Vs values are globally decreasing, possibly suggesting preferential infiltration pathways on this location and subsequent pore pressure increase, whereas the eastern part of the dam still shows slight Vs increase compared to the reference date.

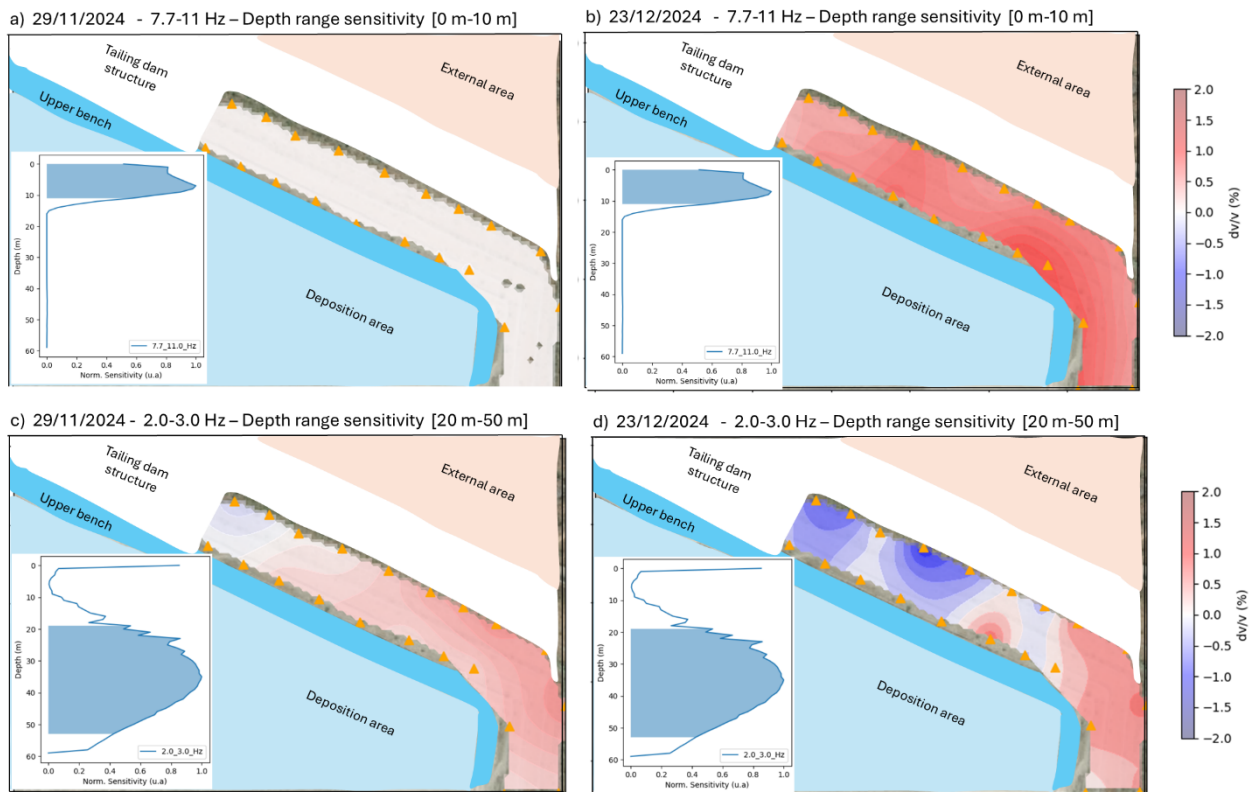


Figure 4. Examples of 2D Vs maps produced for multiple depth ranges and time-steps. a) and b) 2D Vs maps at two different dates with shallow depth sensitivity (0-10 m). c) and d) 2D Vs maps at two different dates with deeper sensitivity (20-50 m). Reference date for relative variation computation is 19/11/2024.

Evolutionary Depth profiles

Another imaging procedure based on inversion processes allows for retrieving the evolution in time of Vs values related to depth around a given seismic sensor location. Such inversion processes take advantage of the depth sensitivity distribution presented in Figure 2b) to transform Vs variations time series associated with multiple frequency ranges into a temporal matrix that describes how Vs varies in time and depth, with a volumetric sensitivity around each location of the dam where a seismic sensor is installed.

Figure 5 illustrates such imaging for the sensor 7B-1, which is located at the top of the dam, close to some VWP installations. A first noteworthy feature of this visualisation is the highlighting of dam layers

where V_s is globally increasing versus layers where V_s is decreasing. In tailings dam monitoring context, V_s decrease can usually be attributed to pore pressure increase, for instance associated with phreatic surface level elevation, whereas V_s increase can possibly denote compaction processes enhancement or desaturation effects. Hence, Figure a) and Figure b) potentially highlight multiple physical behaviours occurring within the dam. The transition zone between layers with positive or negative V_s variations possibly indicates an estimate of the phreatic surface level, as suggested by comparison with estimated phreatic surface level evolution based on VWP measurements. Another interesting feature of this image is the alternance of positive and negative variations in the shallow part of the model (0-5 m) which may relate to alternance of deposition periods and drying periods and may also reflect the effect of precipitation events in November and December 2024.

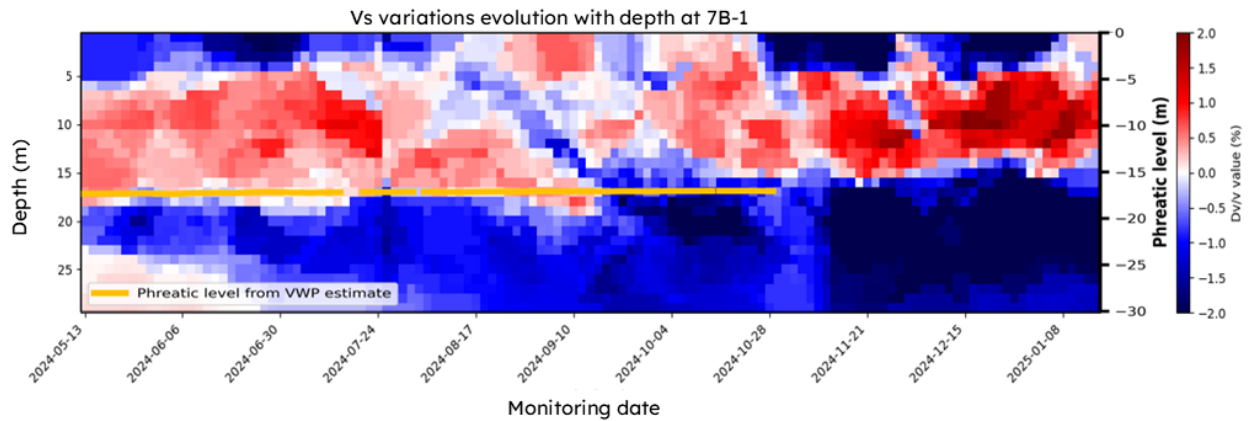


Figure 5. Temporal matrix of V_s variations in depth at the location of sensor 7B-1. The yellow line indicates the phreatic surface level evolution at the same location based on VWP estimates.

Hence, visualising V_s variations in depth provides an understanding of the hydrogeological and geotechnical response of the different compartments of the tailings dam structure and provides a way to estimate the absolute phreatic surface level at any location of the dam where a seismic sensor is installed.

MONITORING – MICROSEISMIC SURVEILLANCE

Understanding the seismic environment of geotechnical assets such as tailing dams supports a better understanding and knowledge base. Continuous seismic monitoring allows for a near real-time classification of seismic events by their waveforms, amplitudes (peak particle velocity for instance) and any other characteristics. Figure 6a illustrates a now classical approach based on template matching. A seismic event is chosen as a template and is correlated with the complete time-series to identify similar events occurring every now and then in the dam. In this example, the similarity of the waveforms is higher than 90%, which suggests that these events share similar physics and plausibly have a common origin and location. By multiplying the templates and performing a thorough analysis of the recordings, it becomes possible to identify areas within the dam prone to producing seismic events, i.e., a must-have information for the engineers.

Seismic events occurring in the immediate vicinity of the structure can have several effects. In the first place, even moderate shakings (moderate earthquakes, or blasts) can trigger small seismic events inside the structure that underlie the brittle behaviour of parts of the dam. In addition, moderate shakings can excite the resonance of the tailing dam and trigger a transitory response of the structure; a small decrease in the resonance frequency followed by a recovery to the initial state. In the worst-case scenario, strong shaking may induce permanent damage that translates into a permanent decrease in the fundamental frequency. Figure b illustrates the impact of a nearby blast sequence on the tailing dam. The blast

recording is transformed using a continuous wavelet analysis to reveal the time-frequency pattern of the ground motion. Before the occurrence of the blast, the wavefield is dominated by 10-30 Hz waves. At 20s the blast is recorded and radiates seismic energy from 3 to 300 Hz. This energy rapidly decays and soon after the blast sequence we retrieve the dominance of the wavefield by the 10-30 Hz range. In the dozens of seconds following the blast's strong shaking, we identify a gain of energy around 5 Hz, which is close to the fundamental frequency measured at this station. This observation means the blast sequence was strong enough to excite the resonance of the dam for about 40 seconds. Those results illustrate the utility of a permanent survey of the impact of blasts and strong shakings on the structural integrity of the tailing dam.

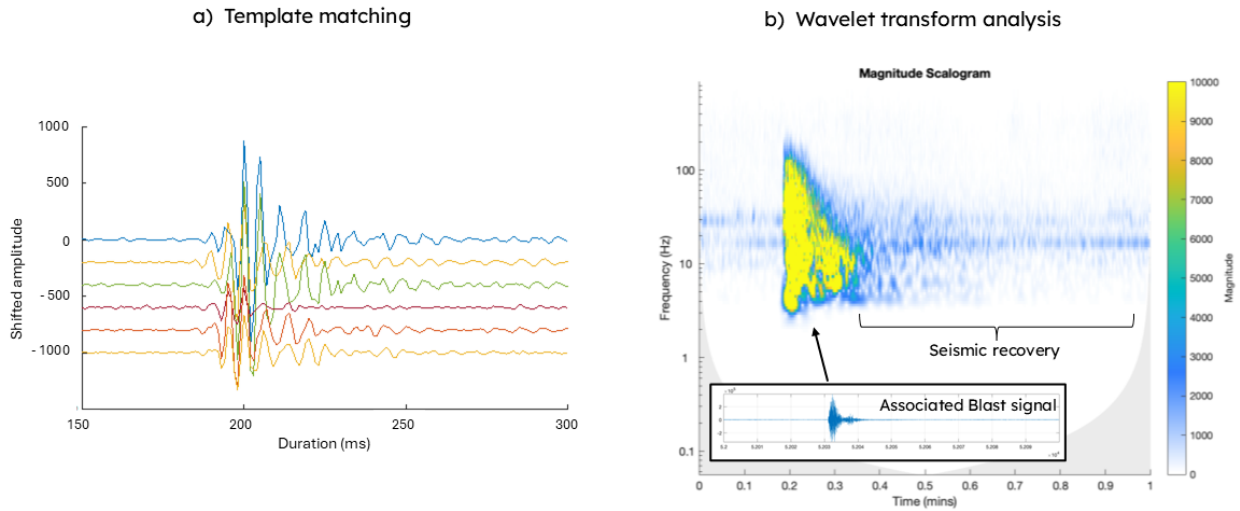


Figure 6. a) Illustration of template matching performance to identify seismic events with the same origin. Six different seismic signals with coherency > 0.9 were identified within the same day. b) Illustration of wavelet transform analysis for assessment of structural and recovery response to seismic events.

CHARACTERISATION - RESONANCE FREQUENCY AND DAMPING RATIO

Resonance frequency and damping ratio are two geotechnical parameters that describe the seismic behaviour of geotechnical assets. Resonance fundamental frequency can be derived from the analysis of horizontal to vertical spectral ratios (HVSr) computed on passive seismic noise recordings. The spectral ratio between the horizontal and vertical components of the noise signals exhibits maximum amplitude at the frequency associated with the fundamental resonance mode. The fundamental frequency identified in HVSr is generally associated with the strongest amplification factor, which means that the seismic response of the dam at this frequency will be strongly amplified and that seismic events with high energy levels at those frequencies should be particularly scrutinised as should their effect on the geotechnical asset health status post-event. Along with the amplification factor, engineers should also determine the damping ratio to complete the modelling of the seismic response of the dam to a strong shaking. Here again, continuous seismic noise measurements can be used to infer the damping factor of soil through the random decrement technique (Castaletto *et al.*, 2024).

Figure 7 (left) shows a map of fundamental frequency values measured at each location of the 3C sensors array deployed at the tailings dam surface. The distribution of values well reflects the structure of the dam, with low fundamental frequency at the top (thick resonating layers) and higher values moving toward the toe or outside the dam (thin resonating layers). One can also observe variations along the longitudinal direction of the wall, indicating potential differences in the internal layering and structure of the dam. Such observations can be useful in comparison with other geophysical characterisation investigations to support lateral heterogeneity identification and interpretation. Figure 7 (right) shows examples of damping ratios values computed for a subset of the sensor array, for each respective fundamental frequency value. Observed damping ratios are also consistent with the dam structure

evolution from top to toe, with lower damping ratios at locations of the wall where less attenuating tailings material are present.

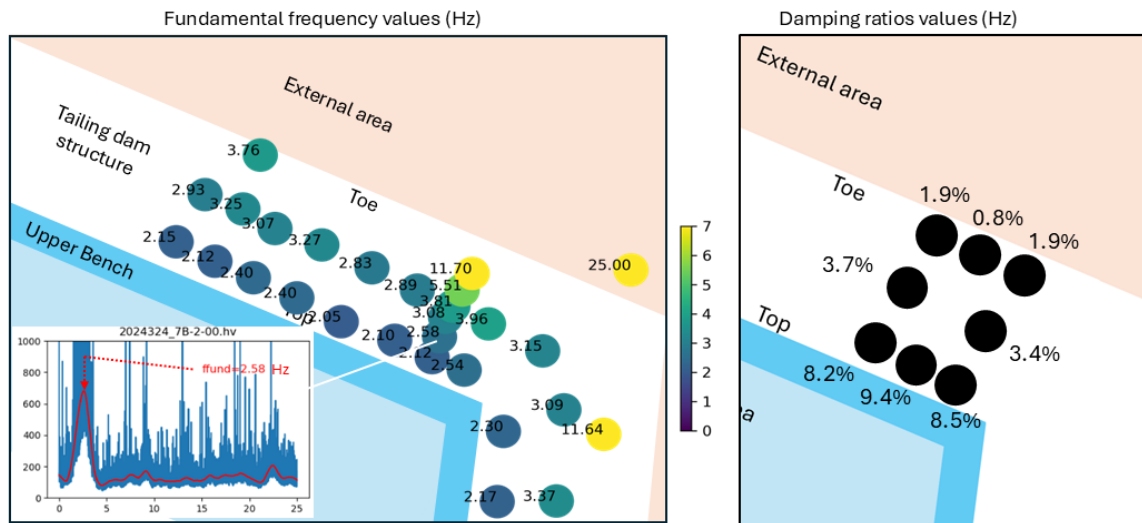


Figure 7. Left: Distribution of fundamental resonance frequency value measured for the whole array of sensors. Right: distribution of damping ratios values measured for a subset of the array during an initial phase of the project.

When used for geomechanical modelling purposes or put in comparison to microseismic analysis, both fundamental frequency and damping ratios can help anticipate the seismic response of the geotechnical asset and hence improve its management. When measured over a large array of sensors, with multiple positions, those measurements also provide insight into the lateral heterogeneities of the internal structure of the asset.

CONCLUSIONS

In this paper we have demonstrated how passive seismic measurements of the ambient seismic noise signal can be multi-purposed to bring high-value information supporting the characterisation and performance monitoring strategies of geotechnical assets such as tailings dams. The integrated solution that we propose uses one unique ambient seismic noise dataset to provide:

- **Microseismic surveillance**, following two distinct objectives:
 - Microseismic classification allows understanding the seismicity characteristics of the local and regional environment of the geotechnical asset, providing classification of the various seismic and microseismic events occurring in the area.
 - Response analysis to significant seismic events. Spectral analysis tools can help monitor the asset response following important seismic events, verifying a full recovery of the structure or indicating how it may be ageing or degrading.
- **Seismic and geotechnical characterisation**: Measuring geotechnical parameters such as fundamental resonance frequency and damping ratio values, at any location where a seismic sensor is installed, assisting engineers to anticipate through seismic response modelling how the structure will react to seismic solicitations. Note that another noteworthy seismic characterisation process that we did not address within this paper can also be derived from ambient noise signal using ANSI approach. This process is referred to as ANSI tomography (e.g., Gerrit *et al.*, 2018) and provides a 2D or 3D static model of Vs values.

- **Seismic monitoring through ANSI application:** Providing spatial and temporal quantification of seismic Vs variations, which are known to be primarily sensitive to pore pressure evolution and geomechanical evolution. We have shown that the passive seismic Vs monitoring approach provides additional and complementary tools to:
 - Track the evolution of hydrogeological parameters: Mapping variations that are due to external events (e.g., precipitation) or mining operations (e.g., tailings deposition), within and throughout the asset.
 - Monitor the relative changes in phreatic surface level: This is achieved with a vertical accuracy and resolution in the order of 2 cm.
 - Estimate the absolute phreatic surface level depth.

The most innovative and useful feature associated with those Vs change measurements and their physical sensitivity is the capacity of the solution to provide images of the associated phenomena, both in lateral and depth dimensions, opening the way to an accurate tracking of hydrogeological and geotechnical parameters anywhere on and within the geotechnical asset using only non-invasive, passive seismic sensors.

In conclusion, the integrated passive seismic solution presented in this paper can serve multiple objectives, from seismic characterisation to seismic monitoring, taking advantage of volumetric sensitivity features to provide a full spatial and temporal coverage of the asset. The direct link between Vs measurements and hydrogeological parameters illustrates the complementarity of this solution with the existing geophysical, geotechnical and hydrogeological tools, leading to safer and more effective dam management practices.

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A development roadmap for the digitalisation of mining focusing on the impact of smart wearables on occupational health and safety

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This paper presents a roadmap for adopting smart wearable technologies to enhance occupational health and safety (OHS) in South Africa's gold and platinum mining sectors. Conducted under the Real-Time Information Management System programme of the Mandela Mining Precinct, the research explores the role of smart wearables in advancing real-time safety monitoring and hazard detection. Despite the global uptake across industries such as healthcare and construction, adoption in South African mining remains limited due to regulatory, technological, and workforce-related challenges. Using literature review and stakeholder interviews across government, industry, trade unions, and academia, the paper identifies key barriers and enablers. The resulting roadmap is structured around three pillars: technological advancement, digital and OHS maturity, and policy and regulation. Recommendations include the establishment of a digital innovation hub, co-designed pilot programmes, and regulatory updates. This roadmap supports a just, inclusive, and ethical transition toward zero-harm mining through the effective integration of smart wearables.

Keywords: digitalisation, smart wearables, development roadmap, mining

INTRODUCTION

South Africa's mining sector is undergoing a digital evolution aimed at aligning with the Fourth Industrial Revolution. This transformation focuses not only on increasing productivity and operational efficiency, but also on improving occupational health and safety (OHS). Among the technologies driving this change, smart wearables have emerged as a crucial innovation, offering real-time data collection and monitoring that support the zero-harm objective of the mining industry (Mardonova & Choi, 2018; Atif *et al.*, 2020).

The mining industry remains one of South Africa's most critical economic sectors, contributing significantly to GDP, employment, and foreign exchange earnings. As of 2023, the sector included over 500 mines producing a wide array of minerals, notably gold, platinum, and coal (Africa Mining IQ, 2024). However, the sector continues to face numerous challenges including fluctuating commodity prices, rising operational costs, environmental sustainability mandates, and – most significantly – persistent health and safety incidents (PwC, 2023).

Occupational injuries and fatalities, especially from fall-of-ground events and transportation incidents, continue to occur despite longstanding regulatory frameworks and collaborative safety initiatives. Mineworkers also face a triple burden of disease, encompassing occupational illnesses, communicable diseases such as tuberculosis and HIV, and non-communicable conditions exacerbated by harsh working environments (Coulson & Christofides, 2020).

These complex health risks necessitate proactive, data-driven safety and health systems that go beyond traditional protective equipment and reactive measures.

Digital technologies have already started transforming mining globally. In South Africa, efforts to digitalise mining operations have led to innovations in autonomous vehicles, real-time environmental monitoring, and smart control centres (Shimaconda-Nawa & Nwaila, 2024). Smart wearables—digital devices integrated into helmets, vests, boots, and face masks—represent a growing frontier of this transformation. These devices can monitor biometrics such as heart rate and fatigue, environmental parameters like gas concentrations, and worker location, enabling predictive and real-time responses to hazardous situations (Hanuska *et al.*, 2016; Slater, 2017).

Despite the demonstrated benefits and successful pilots, the adoption of smart wearables remains slow in South African mines. This is attributed to a variety of interlinked challenges, including inadequate underground connectivity, lack of standardised performance benchmarks, low digital literacy among workers, and concerns over privacy and surveillance (Ndlovu *et al.*, 2022; Jacobs, 2017; Ruotsalainen & Blobel, 2020). Resistance from trade unions and workers also reflects broader apprehension about job security, technological exclusion, and ethical oversight in a rapidly digitising industry (Hlatshwayo, 2017). Table 1 depicts the awareness and utilisation of smart wearable devices. In addition, Table 1 showcases the research findings obtained through the outlined methodology.

Table 1. Application of smart wearables in the South African mining industry

Wearable Type	Use cases/applications	Stakeholder knowledge and awareness	Evidence of pilot testing and/or adoption of SA gold/platinum mining
- Smart helmet - Smart headband	- Fatigue monitoring - Hazardous gases detection - Humidity measurement - Temperature measurement	Highly aware and knowledgeable of the applications for OHS.	Yes, research and pilot testing for fatigue in a gold mine operation.
- Smart watches - Fitness trackers	- Activity tracker - Fitness tracker - Heart rate monitor - Navigation - Physiological wellness - Temperature measurement	Highly aware and knowledgeable of the applications for OHS.	Yes, research and pilot testing for fatigue in a gold mine operation.
- Smart glasses - VR glasses - VR headsets	- Barcode scanners - Location mapping - Instant immersion into other environments - Simulation-based training	Highly aware and moderately knowledgeable about some OHS applications.	Yes, research, training and pilot testing in a gold mine operation.

• Smart face mask and shield	- Biosensors - Infection mitigator	Highly aware and moderately knowledgeable about some OHS applications.	There is no evidence of a smart face mask and shield with embedded biosensor.
• Safety vests • Smart shoes	- Body position tracking - Heart rate monitor - Illumination - Mobility Monitoring - Proximity detection - Temperature measurement	Yes, moderately aware and limited familiarity with applications for OHS.	Yes, it is currently in the research phase.
• Wearable camera	- Environment monitoring - Real-time photo and video capture	Highly aware and knowledgeable of the applications for OHS.	Yes, it is currently in the research phase
• Smart jackets • Smart rings	- Temperature measurement - Body movements	Yes, low awareness and limited familiarity with applications for OHS.	No evidence was reported.
• Industrial exoskeleton	- Physical support	Yes, moderately aware and limited familiarity of applications for OHS.	Yes, is currently in pilot testing.

In addition, while the global mining industry increasingly integrates wearable technologies into safety systems, South African personal protective equipment guidelines have yet to formally incorporate such innovations, revealing a regulatory lag (Department of Mineral Resources and Energy, 2023). As such, there is a growing urgency to build a robust roadmap for adoption that aligns technical development with regulatory support and inclusive stakeholder engagement.

Parallel to the mining industry, smart wearables have emerged as a transformative tool in industries with high-risk environments analogous to mining—such as construction, oil and gas, and heavy manufacturing—where workers routinely face hazards including extreme temperatures, noise, exposure to gases, repetitive physical strain, and isolated conditions. These devices typically include biometric sensors, GPS trackers, smart helmets, fatigue monitoring headbands, and environmental detectors, all designed to collect real-time physiological and situational data. Their integration into industrial safety protocols allows for continuous monitoring of vital signs (e.g., heart rate, body temperature), worker location, posture, and exposure to hazardous elements like toxic gases or radiation. This real-time feedback enables supervisors and OHS personnel to intervene proactively, preventing accidents before they occur and ensuring a rapid response to emergencies (Sawhney *et al.*, 2020; Shin *et al.*, 2019).

In the construction sector, smart wearables have demonstrated measurable safety benefits. For instance, smart helmets with embedded inertial sensors have been used to detect falls and alert supervisors instantly, while smart vests equipped with vibration sensors warn workers of dangerous machinery

proximity. These tools have contributed to significant reductions in workplace injuries and improved worker situational awareness (Sawhney *et al.*, 2020). Similarly, in the oil and gas industry, smart wearables are used to detect the presence of hydrogen sulphide and other harmful gases. Devices can be integrated with wireless networks to provide centralised dashboards that track workforce health and safety metrics across large, remote worksites, enabling both on-site and off-site safety oversight (Shin *et al.*, 2019).

In manufacturing, smart glasses and wristbands are commonly used to monitor fatigue and stress levels, which are critical in preventing cognitive overload in machine-intensive environments. These devices provide subtle alerts to the worker and management when fatigue thresholds are exceeded, allowing rest breaks to be scheduled more effectively. Moreover, integrating wearable data with enterprise systems enables predictive maintenance and reduces unscheduled downtime by identifying patterns linked to worker strain or unsafe behaviours (Wang *et al.*, 2021).

Beyond individual worker safety, smart wearables contribute to organisational benefits such as reducing insurance claims, improving regulatory compliance, and lowering compensation payouts. Data collected from wearables also feed into data analytics platforms, enabling the identification of trends, high-risk tasks, or times of day when incidents are more likely to occur. This fosters a data-driven safety culture, where interventions can be designed based on evidence rather than assumptions. These technologies are especially valuable in industries undergoing digital transformation aligned with Industry 4.0, where real-time monitoring, automation, and predictive analytics are integrated into operational and safety strategies.

Given these demonstrated benefits in parallel industries, the mining sector stands to gain considerably from the adoption of smart wearable technologies. Mining operations can replicate these safety enhancements by deploying rugged, miner-specific devices capable of operating in deep, humid, and dust-laden environments. Furthermore, by coupling wearables with underground communication networks and centralised control systems, mines can achieve real-time worker visibility, enhance emergency response capabilities, and reduce the frequency and severity of injuries—ultimately contributing to their zero-harm goals and more efficient, resilient operations.

This paper, based on research conducted under the Real-Time Information Management System (RTIMS) programme of the Mandela Mining Precinct, presents such a roadmap. Drawing on stakeholder interviews, literature analysis, and case examples, it outlines a structured path towards digital OHS transformation in South African mining. The roadmap is underpinned by three pillars: technological advancement, digital and OHS maturity, and regulatory alignment.

METHODS

The methodology comprised of a four-step approach was adopted:

1. **Literature Review:** An extensive review was conducted to understand global trends in mining digitalisation and the use of smart wearables in hazardous environments. This informed an assessment of wearable technology adoption in South Africa's gold and platinum mines and shaped the design of stakeholder interview questions.
2. **Stakeholder Engagement:** With ethical clearance from the University of the Witwatersrand (Ref. H24/10/09), eight semi-structured interviews were conducted across key stakeholder groups—government, industry, academia, and civil society (trade unions). Trade union representatives, comprising 38% of interviewees, provided valuable insights into end-user perspectives.
3. **Insights Analysis:** Data from literature, industry reports, media sources, and stakeholder interviews were thematically analysed. This process helped refine the conceptual framework and uncover key barriers to wearable technology adoption.
4. **Roadmap Development:** Insights from the analysis informed the creation of a strategic roadmap. Key enablers were mapped across the transition from traditional to modern mining

environments to support the equitable and practical adoption of smart wearables for OHS enhancement.

Although the research employed a qualitative methodology through semi-structured interviews, which provided rich, in-depth insights into stakeholder experiences and perceptions, the study could have been further strengthened by incorporating a quantitative component. Specifically, a statistical analysis of smart wearable adoption trends across the mining industry—as well as related sectors such as construction, oil and gas, and manufacturing—could have provided broader empirical evidence to support the qualitative findings. This would have enabled the researchers to identify patterns, usage rates, and performance metrics of wearable technologies, enhancing the validity and generalisability of the results.

Additionally, expanding the scope and number of stakeholder engagements could have yielded a more comprehensive representation of industry perspectives. Engaging a broader set of participants, including frontline mineworkers, technology developers, health and safety regulators, and union representatives, would have allowed for greater triangulation of data. Such diversity in viewpoints may have uncovered additional barriers, opportunities, and context-specific considerations that could inform the digitalisation roadmap with more precision. For instance, the inclusion of more female miners or contract workers could have highlighted unique ergonomic or equity challenges that may not be visible in management-level insights alone.

Ultimately, complementing the qualitative findings with quantitative data and expanded stakeholder diversity would have enriched the roadmap's design by offering a more nuanced and data-driven foundation for policy recommendations, strategic planning, and technology deployment in the adoption of smart wearables for occupational health and safety in the mining sector.

OUTPUTS

The consolidation of data from the literature review and from stakeholder engagement resulted in revisions to the underlying conceptual framework for this study (refer to Figure 1). Analysis of the research findings resulted in three overarching themes and barriers contributing to adopting smart wearables in the South African mining industry. These are 1) technological advancements related to smart wearables; 2) digital and OHS maturity; and 3) policy and regulation in the South African mining sector. The nested approach emphasises the linkages and dependencies across the three themes, which are technology advancements and smart wearables driving digital and OHS maturity. Whilst digital and OHS maturity impacts the development of policy and regulation, whereby policy and regulation strive to standardise validated technologies. Furthermore, indicating the difference between sector versus organisational implications is necessary to differentiate how the industry can evolve and what specific organisations/operations can implement. For example, from an industry perspective, the insights concluded that OHS policy and regulation will either hinder or accelerate smart wearable adoption. Similarly, innovations for smart wearables at a mine operational level catalyse industry-wide change and not vice versa. Thus, to optimise and accelerate industry-wide adoption of smart wearables it is essential to ensure that sector-wide processes proactively contribute to the adoption of technology. This study found that the biggest gap in the adoption of smart wearables is in the sector-wide response, in contrast to operational level, where there already is evidence of significant levels of interest, piloting and varying degree of technological adoption.

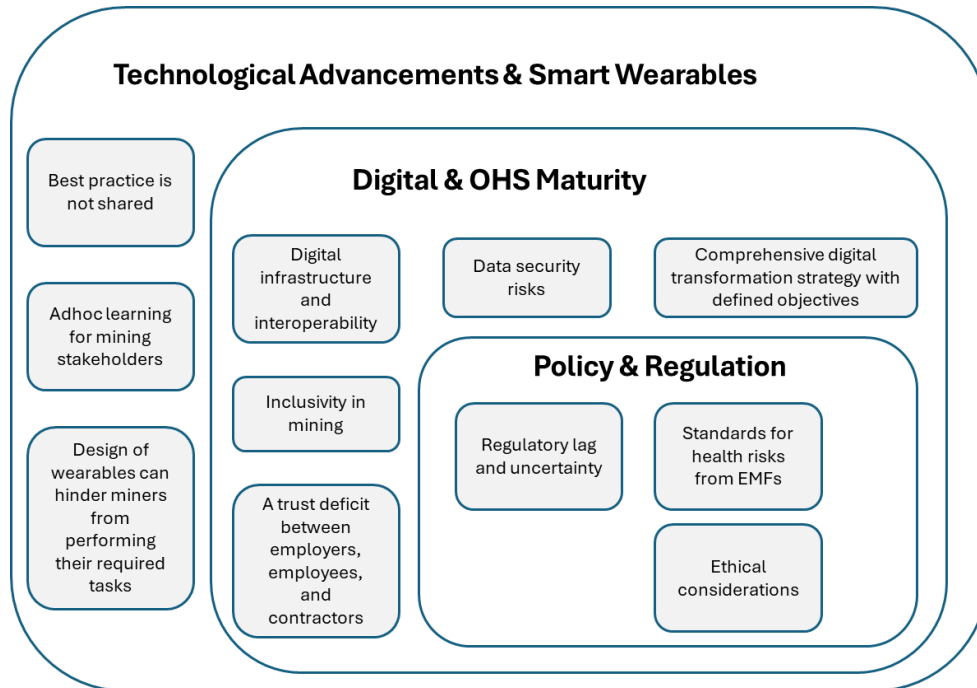


Figure 1. Conceptual framework for digitalisation in South African mining.

Figure 1 illustrates the relationship between the three overarching themes identified in this study. The study concludes that successful digitalisation involves exchanges between technological advancements, digital and OHS maturity, and policy and regulation. With regards to digitalisation in South Africa's mine sector, micro-level changes at an operational level impact the macro-level, political, and regulatory environment. Therefore, digital and OHS maturity impacts policy and regulation development, whereby policy and regulation strive to standardise validated technologies.

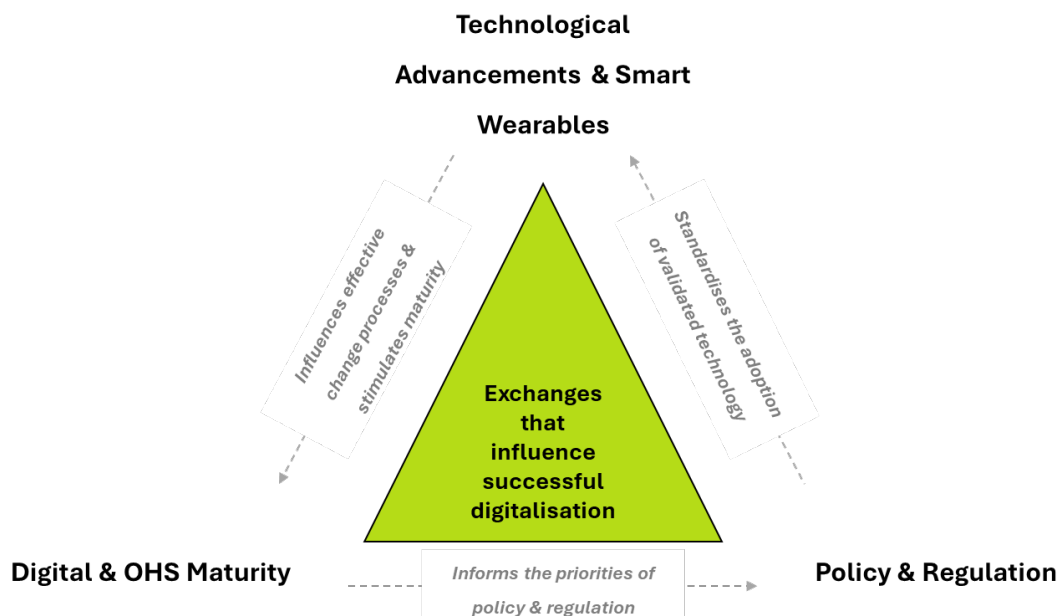


Figure 2. Linkages between digitalisation pillars.

Each pillar contains specific challenges and considerations regarding adopting digital technology, specifically smart wearables, across the South African gold and platinum mining sector. Associated with these barriers are sector-wide and organisation-wide development enablers that catalyse the adoption of technology. Table 2 below represents these various factors, which are then translated into a visual roadmap (Figure 3).

The digital transformation roadmap outlines a structured progression for integrating smart wearables for OHS impacts in South Africa's gold and platinum mining sector. It categorises the transition from traditional mining to hybrid mining and ultimately to modern mining. It focuses on three key pillars: Technological Advancements and Smart Wearables, Digital and OHS Maturity, and Policy and Regulation. The roadmap also differentiates between sector-wide initiatives that drive industry collaboration and organisation-level actions that individual mines could adopt.

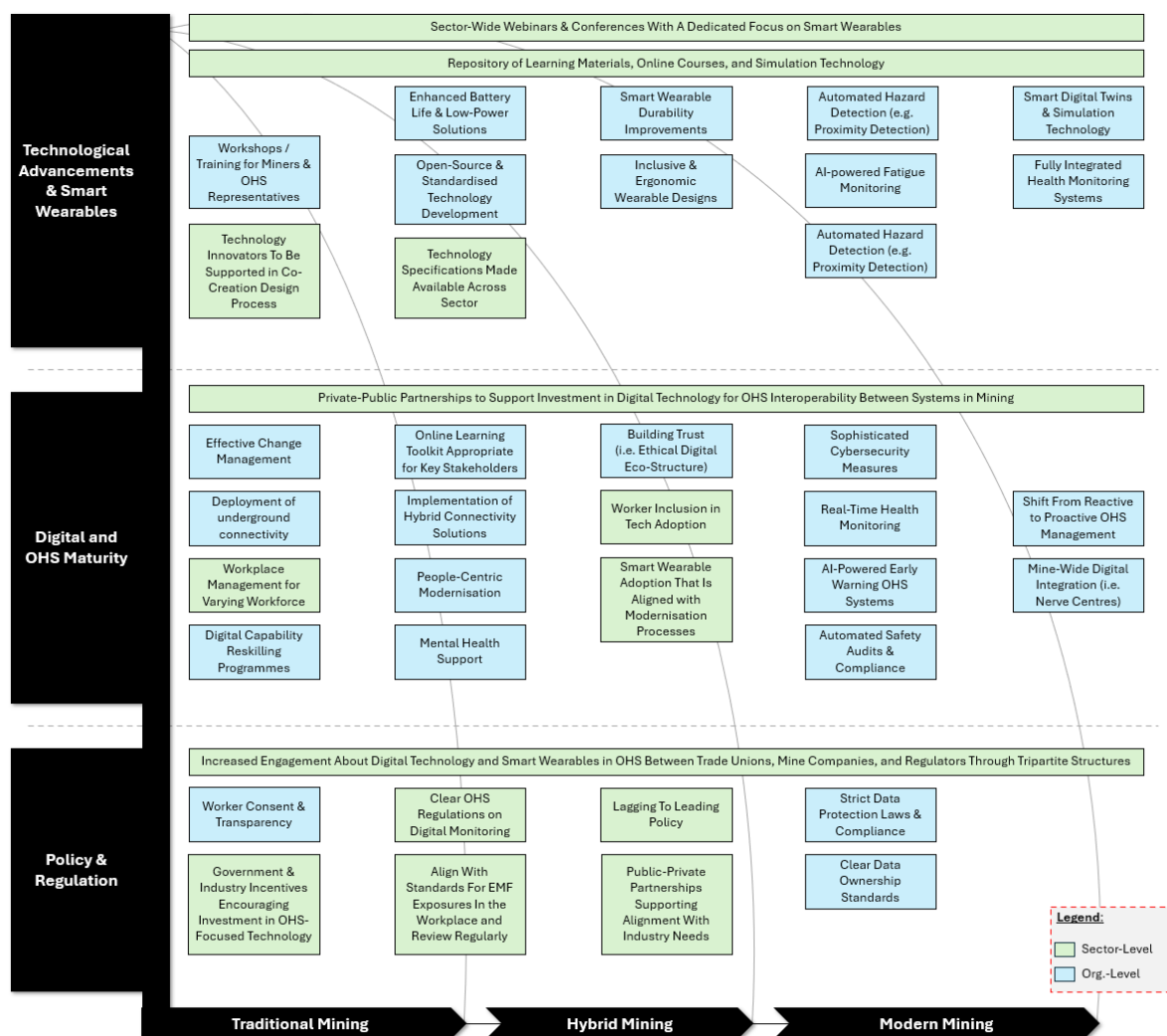


Figure 3. Digitalisation roadmap for the adoption of smart wearables to support OHS in South Africa's mining industry.

Table 1. Digitalisation and smart wearable adoption enablers

Group	Description	Barriers To Adoption	Sector-Level Adoption Enablers	Organisational-Level Adoption Enablers
Technological Advancements and Smart Wearables	The adoption of advanced wearables will facilitate a data-driven digital ecosystem, enhancing productivity and occupational health and safety while reducing human exposure to hazardous conditions. Furthermore, this refers to improvements to the reliability, accuracy, ergonomics, and user-inclusivity of smart wearable technologies.	Best practice is not shared	Sector-wide webinars and conferences include a dedicated focus on smart wearables, the use of real-time data and AI in OHS.	Fully integrated health monitoring systems: Wearables (including smart devices and textiles) could provide real-time worker health insights, allowing early intervention for fatigue, stress, and hazardous exposure. Automated hazard detection: AI systems could use real-time data to predict and prevent risks, such as fatigue-related incidents, gas leaks, and seismic activity. AI-powered fatigue monitoring: AI models could learn from worker behaviour, ensuring accurate fatigue detection without false positives.
		Ad hoc learning for mining stakeholders	Access to information: Repository of learning materials, online courses and simulation technology available to all stakeholders. Access to information: An online learning package/toolkit appropriate to all stakeholders: employers, trade unions and the regulator, including at mine operations.	Open-source and standardised technology development: Developing shared platforms for wearables can reduce costs and increase accessibility. Smart digital twins and simulation technology: Digital mine replicas can enable risk scenario testing and training simulations. Workshops/training made available to worker representatives and mine health and safety committee.
		Design of wearables can	Co-creation: Technology innovators may be	Smart wearable durability improvements: Devices must

Group	Description	Barriers To Adoption	Sector-Level Adoption Enablers	Organisational-Level Adoption Enablers
		hinder miners from performing their required tasks	supported by the end users in the co-creation design process. • Access to information: Technology specifications can be made available across the sector, including updating guidance on PPE to support best practices.	withstand extreme underground conditions (humidity, dust, heat, vibrations). • Enhanced battery life and low-power solutions: Longer battery life will reduce frequent charging requirements. • Inclusive and ergonomic designs: Wearables should be lightweight, flexible, and adaptable for various mining environments and genders. Equipment and PPE should fit female miners, ensuring comfort and usability.
Digital and OHS Maturity	The integration of smart wearables depends on the digital readiness of mining operations, including connectivity infrastructure, workforce digital skills, ethical and privacy maturity, and automation adoption. Increasing real-time monitoring, predictive analytics, and AI-driven safety interventions will enhance OHS and operational efficiency as mines transition from traditional to modern.	Digital infrastructure and interoperability	• Increase awareness: Sector-wide webinars and conferences include dedicated focus on smart wearables, the use of real time data and AI in OHS. • Partnerships: Public-private partnerships to support investment in digital technology for OHS and interoperability between systems in the gold and platinum sectors.	• Deployment of underground connectivity/networks: This will enable real-time monitoring, data sharing, and AI-driven decision-making. • Implementation of hybrid connectivity solutions: RFID, LiDAR, and edge computing can process data locally, reducing dependency on constant network availability. • Mine-wide digital integration (e.g. Nerve Centres): A centralised data-sharing system could allow health, safety, and production departments to collaborate more effectively. • AI-powered early warning systems: Wearables could be linked to predictive analytics that can prevent hazards before they occur.

Group	Description	Barriers To Adoption	Sector-Level Adoption Enablers	Organisational-Level Adoption Enablers
				newly adopted digital technologies and possible work intensification.
		Inclusivity in mining	• Co-creation: Technology innovators may be supported by the end user in the co-creation design process. • Access to information: Technology specifications to be made available across the sector, including updating guidance on PPE to support best practices.	• Worker inclusion in technology adoption: Miners should be actively involved in decision-making on wearable implementation including women miners.
		Comprehensive digital transformation strategy with defined objectives	• Aligned transformation: The adoption of smart wearables to be aligned and integrated with other modernisation processes.	• Digital capability reskilling programs: Training in AI, automation, and digital safety tools can help workers adapt rather than be displaced. • Understand the user (people-centric modernisation): Critical to adopting technology is understanding the resistance factors inhibiting technology adoption, coupled with organisational behaviour factors, which could improve the probability of a successful adoption. • Effective change management: Clear, comprehensive, and transparent change management strategies are needed to introduce new technology into operations successfully.

Group	Description	Barriers To Adoption	Sector-Level Adoption Enablers	Organisational-Level Adoption Enablers
				• Shift from reactive to proactive safety management: Mines may prioritise accident prevention over incident response. • Sophisticated cybersecurity measures: As mines adopt 4IR technology, specifically IoT, the increased reliance on data exchange raises the risk of cybersecurity threats. More advanced cybersecurity measures are needed to protect data in a significantly more digitally connected environment.
		Data security risks	• Access to information: Technology specifications can be made available across the sector, including on data security. • Cybersecurity guidance: Policy development and guidance about ethical practice in OHS digitisation.	
Policy and Regulation	Establishing clear regulatory frameworks and compliance standards is essential to guide the responsible adoption of smart wearables, ensuring data privacy, and ethical surveillance, and workforce protection while aligning with OHS regulations and digital transformation policies in the mining sector.	Regulatory lag	• Lagging to leading: Fast-track policy that considers the implications of future technological advancements rather than reacting to what is occurring. • Clear OHS regulations on digital monitoring: The DMRE could provide structured guidelines on the implementation and governance of wearables • Ethical digital-eco structure guidance: Policy development and guidance about ethical practice in OHS digitisation.	• Data protection laws (POPIA compliance): Strict policies must be enforced to ensure data security, ownership, and ethical use.
		Ethical considerations		• Worker consent and transparency: Employees should understand how their data is collected, used, and stored. • Data ownership: Certainty over who controls and accesses health-related

Group	Description	Barriers To Adoption	Sector-Level Adoption Enablers	Organisational-Level Adoption Enablers
			Access to information: An online learning package/toolkit appropriate to all stakeholders: employers, trade unions and the regulator, including mining operations.	data. As well as how it can be used within the workplace.
		Standards for health risks from EMFs	Alignment and review of EMF standards: Standards and guidance about EMF exposures in the workplace to be regularly reviewed.	
		Structured collaboration across key stakeholders	Increased collaboration: Greater engagement between unions, companies, and regulators through tripartite structures regarding smart wearables and digital technology in OHS will support wearables being used for health and safety, not surveillance and work intensification. Government and industry incentives: Tax breaks and funding programmes could encourage investment in OHS-focused technology. Public-private partnerships:	

Group	Description	Barriers To Adoption	Sector-Level Adoption Enablers	Organisational-Level Adoption Enablers
			Collaboration between government agencies, technology providers, and mining companies can drive cost-effective innovation.	

Technology Advancements and Smart Wearables

The first pillar highlights developing and deploying wearable technologies, AI-driven monitoring, and training to enhance worker safety. In traditional mining, the absence of standardised smart wearables and real-time monitoring systems limits safety capabilities. At this stage, the focus is on training miners and OHS representatives, developing open-source technology standards, and encouraging collaboration between technology innovators and mining operators to design wearables suited for traditional mining environments.

As the industry transitions to hybrid mining, key advancements include improved wearable durability, enhanced battery efficiency, and gender-inclusive ergonomic designs to ensure practical adoption. At this stage, automated hazard detection (e.g., proximity sensors) and AI-powered fatigue monitoring are introduced to mitigate workplace risks.

In modern mining, the implementation of smart digital twins and fully integrated health monitoring systems transforms OHS management. These technologies provide real-time hazard detection, predictive safety analytics, and proactive intervention mechanisms, minimising human exposure to hazardous conditions. The technological evolution in this pillar ensures that wearables and AI-driven solutions become core components of a digitally connected and safety-focused mining ecosystem.

Synonymous across mining is the facilitation and hosting of sector-wide webinars and conferences, with a dedicated focus on smart wearables, to enlighten the industry on technological developments, enhancing OHS practices while establishing a learning platform for increased collaboration across the sector.

Digital and OHS Maturity

This pillar focuses on workforce readiness and operational integration of smart safety systems. Traditional mining faces significant challenges, such as limited underground connectivity, a lack of digital workforce skills, and resistance to technology adoption. To bridge these gaps, the focus is on deploying underground connectivity, implementing workforce management strategies for diverse employment models, and initiating reskilling programmes.

In hybrid mining, people-centric modernisation and worker inclusion in technology adoption become crucial for success. Hybrid connectivity solutions (e.g., RFID, LiDAR) enable seamless real-time data transmission to enhance safety monitoring. Additionally, mental health support systems are introduced to mitigate stress related to continuous monitoring.

By the time mines reach the Modern Mining stage, sophisticated cybersecurity measures, AI-powered early warning systems, and automated safety audits are fully operational. The industry shifts from reactive OHS management to a proactive approach, where real-time monitoring and predictive analytics help prevent workplace accidents before they occur. Mine-wide digital integration (e.g. Nerve Centres) ensures seamless coordination of OHS functions across entire operations, making mining safer and more efficient.

Private-public partnerships to support investment in digital technology for OHS interoperability between mining systems are crucial to enhancing digital and OHS maturing. Enhancing collaboration and learning between the tripartite stakeholders could accelerate the adoption of technology across the South African gold and platinum mining sector.

Policy and Regulation

The third pillar addresses the regulatory evolution necessary to support smart wearable adoption and digital OHS transformation. In traditional mining, greater worker consent and transparency regarding digital monitoring are needed. Government and industry incentives are essential to encourage investment in OHS-focused technology, while standards for EMF exposure from wearables must be defined to ensure worker safety.

During the Hybrid Mining phase, regulatory frameworks evolve through public-private partnerships and structured policy alignment with industry needs. The focus is on developing clear OHS regulations for digital monitoring and transitioning from lagging policies to leading policies that actively support digitalisation.

In modern mining, strong regulatory enforcement ensures compliance with strict data protection laws, standardised data ownership guidelines, and ethical AI governance. These policies safeguard worker rights, prevent biometric data misuse, and establish ethical boundaries for digital surveillance in mining. The alignment of policy, regulation, and technology adoption ensures that digital transformation benefits both workers and employers while upholding global safety and labour standards.

This comprehensive digital roadmap ensures that mining operations evolve into technologically advanced, data-driven environments where productivity, worker safety, and regulatory compliance are seamlessly integrated. By addressing policy alignment, workforce adaptation, and technological enhancements, this transformation improves operational efficiency and prioritises worker health and safety, making the mining industry safer, more sustainable, and more progressive.

CONCLUSION AND RECOMMENDATIONS

The adoption of smart wearable technologies in South Africa's gold and platinum mining sector presents a transformative opportunity to enhance OHS. While digitalisation has significantly improved safety monitoring and risk management globally, South Africa's adoption remains slow, hindered by connectivity, technological, regulatory, and workforce challenges. Despite a steady decline in mining fatalities, fall of ground incidents and transportation accidents remain the most significant risks. Smart wearables, including fatigue monitoring headbands, hazard detection systems, and missing person locators, could help mitigate these dangers, enhancing real-time safety monitoring and proactive risk management.

However, sector-wide adoption faces key obstacles. Limited knowledge-sharing, fragmented pilot programmes, and connectivity constraints prevent seamless digital integration. The lack of clear OHS regulations, worker trust issues, and ethical concerns surrounding surveillance further delay progress. Addressing these barriers requires a structured digitalisation roadmap, focusing on technological advancements, improved connectivity, workforce training, and regulatory alignment.

Investment in digital infrastructure, hybrid connectivity solutions, and ethical data management is critical for mining operations to achieve zero-harm targets and future-proof safety practices. Stronger collaboration between industry stakeholders, regulators, and workers will ensure a balanced, inclusive, and effective adoption of smart wearables. A worker-centric, well-regulated, and technologically advanced mining environment will improve safety and productivity and position South Africa as a leader in OHS innovation and sustainable mining practices.

The following recommendations are proposed to facilitate the adoption of smart wearables in OHS for gold and platinum mining.

Recommendation 1: An interest group/hub for digital innovation in OHS is established between the Mandela Mining Precinct (MMP), the Mine Health and Safety Council and the Mining Qualifications Authority. This hub will have a dedicated focus on adopting smart wearables and using real-time data for OHS. The hub will ensure the following activities are undertaken:

- Dissemination of best practices across mining stakeholders through dedicated webinars, conference sessions, simulations, and other learning platforms.
- The identification and scoping of a research agenda to support the development of policy related to ethical practice in adopting smart wearables and using real-time information in OHS.

- Fast-track policy development to ensure ethical practice in adopting smart wearables and using real-time information in OHS.
- Align OHS digital policy with the modernisation agenda across the sector.

Recommendation 2: Preparation of an online toolkit/learning package available to all mining stakeholders (employers, trade unions and the regulator) about advances in smart wearables, the potential for OHS and the advantages and ethical concerns about using real-time data. This can be made available at the mine operation to worker OHS representatives and mine health and safety committees.

Recommendation 3: MMP/industry to support co-creation pilots for the design and adoption of smart wearables with a focus on collaboration with end-users (miners) in each stage of the design and adoption process.

Recommendation 4: The Mine Health and Safety Council in collaboration with the Mine Health and Safety Inspectorate to regularly review, update and disseminate standards for EMF exposure in the mine workplace.

Recommendation 5: The industry should explore public-private partnerships and tax concessions with government partners to support the adoption of smart technology in OHS and digital interoperability between systems across the gold and platinum sectors.

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A comparative analysis of implicit modelling and geostatistical methods for geometallurgical block modelling and resource estimation

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Accurate geometallurgical block modelling improves resource recovery, processing efficiency, and mine planning. This paper compares two modelling methods for geometallurgical block modelling. These are the fast radial basis function (FastRBF) implicit method and the ordinary kriging geostatistical method. The methods were applied to predict total cobalt, bond work index (BWI), and rock quality designation (RQD) in a cobalt deposit. Drillhole and geometallurgical data were composited into two-metre intervals and applied to a $10 \times 10 \times 10$ m block model using Leapfrog Geo. Implicit method produced smoother grade distributions and gradual spatial transitions. This is useful in early-stage evaluations. Geostatistical method captured localised high-grade zones and better represented sharp geological boundaries, particularly for RQD. BWI estimates were similar in central tendency but showed higher variability under implicit method. These differences can influence project decisions. A model's ability to reflect local grade variation or broader spatial trends affects scheduling, energy forecasting, and process design. Model selection should align with data quality, geological context, and project stage. This work evaluated modelling outcomes for the two approaches. Future studies should incorporate detailed error metrics, such as RMSE, MAE, and R^2 , and test these methods across varied deposits. Hybrid models may offer balanced solutions by combining the spatial precision of geostatistical methods with the trend continuity of Implicit methods.

Keywords: geometallurgical modelling, implicit methods, ordinary kriging, resource estimation, geostatistics methods, geometallurgical block modelling

INTRODUCTION

Geometallurgy is a field that combines geology with engineering, metallurgy, and environmental considerations (Bye 2011; Dominy *et al.*, 2018; Ehrig 2013). This integration supports mine planning and improves processing efficiency (Garrido *et al.*, 2018, 2020). Incorporating key metallurgical parameters into orebody models helps to overcome processing challenges and enhances resource extraction, contributing to project profitability (Coward and Dowd 2015). To support this integration, geometallurgical block models are used. A geometallurgical block model is a three-dimensional representation of a mineral deposit. It integrates geological characteristics with grades, as well as key metallurgical attributes such as ore hardness and recovery rates (Deutsch *et al.*, 2016). These models are typically developed using geostatistical estimation methods such as ordinary kriging (OK), implicit modelling, or hybrid approaches that combine machine learning with geostatistics (Abildin *et al.*, 2023). This enables the design of mine plans that optimise ore extraction, blending, and processing while managing technical and operational variability (Dominy *et al.*, 2018). It also helps mining operations identify and mitigate production risks, contributing to more stable economic outcomes (Khorram *et al.*, 2020).

However, there are many challenges associated with geometallurgical block modelling. It must capture the spatial variability of metallurgical and geotechnical features, which is often complex and non-linear (Hoffmann *et al.*, 2022). Many geometallurgical variables—such as recovery, comminution indices, mineral assemblages, and rock types—do not exhibit regular spatial patterns. Obtaining reliable parameter estimates and uncertainty measures is difficult when data is limited and uneven (Garrido *et al.*, 2020). More robust methods are needed to integrate diverse data types and model complex geological structures with greater confidence (Abildin *et al.*, 2023). Despite extensive research on traditional geostatistical, machine learning, and hybrid methods for geometallurgical block modelling, implicit modelling techniques remain comparatively underexplored. In particular, there is a lack of comparative analyses assessing the performance of fast radial basis function (FastRBF) relative to conventional geostatistical methods such as OK. This gap highlights the need for further research into the effectiveness of implicit modelling in accurately estimating critical parameters such as metallurgical recovery and rock quality.

This paper aims to provide practical insights by comparing FastRBF-based implicit modelling with OK for geometallurgical block modelling. FastRBF and OK were selected as representative methods from the implicit modelling and geostatistical categories, respectively. Each represents a single approach within its broader class. The comparison offers practical insights into how these specific methods perform when applied to geometallurgical block modelling. The study focuses on three operationally significant variables: total cobalt (TCo), bond work index (BWI), and rock quality designation (RQD). Model performance is assessed using statistical indicators, swath plots, grade-tonnage curves, and resource estimate tables. The paper also evaluates each method's ability to detect high-grade zones and represent spatial variability at broader scales. While this paper does not propose a new modelling approach, its findings may help practitioners and researchers select modelling strategies that align with geological context, data quality, and project objectives. The results may also inform future efforts to integrate geostatistical and implicit methods with machine learning to further improve the reliability and economic value of geometallurgical models.

METHODOLOGY

Implicit method—Fast Radial Basis Function Review

The FastRBF method is part of a broader family of implicit modelling techniques. It is used for surface reconstruction in fields such as computer graphics and geology (Zhong and Wang 2020). The method was developed to address the computational limitations of traditional radial basis function (RBF) interpolation when applied to large datasets, particularly those exceeding 10,000 constraints (Zhong *et al.*, 2019). FastRBF improves efficiency through a domain decomposition strategy. It divides the dataset into smaller sections, which reduces computational demands. This segmentation also helps maintain or, in some cases, improve accuracy and numerical stability. The method involves selecting a suitable radial basis function from a predefined set of interpolants. The choice of kernel parameters plays a critical role, as it can significantly influence modelling outcomes. In practical applications, FastRBF has proven effective in modelling complex orebody geometries with high processing speeds. In Leapfrog Geo software, FastRBF-based implicit modelling builds on earlier work by Savchenko *et al.*, (1995) and Cowan *et al.*, (2003), who introduced the concept of volume functions. Geological boundaries are represented as volumetric surfaces that define distinct geological domains. These surfaces are constructed through the interpolation of a volume function (McLennan 2007; Rolo *et al.*, 2017). The modelling workflow includes several key steps. These are data validation, compositing, interpolation, and meshing. Morphological constraints are applied during interpolation to improve geological realism (Rolo *et al.*, 2017). The resulting three-dimensional models capture both geological structure and grade variability in a continuous and interpretable format.

Geostatistical Methods—Ordinary Kriging Review

OK is a popular geostatistical method for estimating values at unsampled sites in mineral resource models (Marwanza *et al.*, 2025). It is considered a statistically robust method that yields unbiased estimates with low variation. This is accomplished by using a spatial continuity model, represented by a semivariogram, to calculate interpolation weights (Tavares *et al.*, 2008). OK is used in a variety of

applications, including mineral resource estimates, environmental contamination mapping, and soil management. One of its main advantages is its ability to offer solid geographical forecasts together with estimations of related uncertainty. However, OK has certain limits. It may be difficult to simulate non-linear or non-stationary geological phenomena seen in complicated ore deposits (Ibrahim *et al.*, 2022). Interpolated findings are prone to smoothing effects, which often result in underestimating local high or low grades (Atalay 2024). This smoothing is inherent in the weighing process and the use of geographic averages. Furthermore, data density and geographical distribution have a significant impact on OK performance. Semivariogram modelling needs evenly distributed and representative data. In locations with low sampling or significant geological variety, OK may provide less trustworthy data, limiting its efficacy.

Description of the Drillhole and Geometallurgical Data

This research utilised drillhole data from Iverland Mining's cobalt exploration operation in the Democratic Republic of Congo. The data were initially reported by Mboyo (2018). The original data were collected under industry-standard exploration programmes. They were reported as having undergone appropriate quality assurance and quality control procedures. These included collar validation, downhole survey calibration, and assay verification, as detailed in the original studies. In this work, the secondary data were subject to additional format standardisation and validation before import into Leapfrog Geo. Automated checks were used to detect and correct depth inconsistencies, missing intervals, and data mismatches. Records that could not be reconciled were excluded to preserve the integrity of the modelling. To augment this dataset, geometallurgical data were gathered from the works of Dehaine *et al.*, (2021) and (Mambwe *et al.*, (2022). Laboratory collection of such data is both expensive and logistically challenging. The dataset contains spatial coordinates: Easting (mean, 530120.5), Northing (mean, 8714423.53), and Elevation (mean, 1330.6 m) (Table I). Drillhole depths vary from 77.0 to 287.0 m, with an average of 148.3 m. This research focuses on three key geometallurgical variables. TCo has a mean grade of 0.8%. The BWI has a mean value of 11.12 kilowatt-hours per tonne. RQD has a mean value of approximately 49.58%. The drillholes were bored with a mean azimuth of around 114° and a dip angle of 56°.

Table I. Statistical summary of drillhole and geometallurgical data

8,5	X (DD)	Y (DD)	Z (m)	Depth_max (m)	Depth_From (m)	Depth_To (m)	TCo (%)	BWI (kWh/t)	RQD (%)
count	66.0	66.0	66.0	66.0	4717.0	4717.0	4717.0	1122	1122
mean	530120.5	8714424	1330.6	148.3	80.9	81.6	0.8	11,12	49.58
Std	131.9	139.46	0.9	45.4	36.8	36.8	1.8	4,48	20.34
Min	529863.8	8714125.11	1328.9	77.0	2.0	2.4	0.0	0	0
25%	530027.7	8714329.56	1329.9	116.6	52.2	52.8	0.1	7	36.33
50%	530123.0	8714419.35	1330.6	144.8	79.5	80.4	0.2	12	54.74
75%	530218.6	8714518.54	1331.3	170.0	107.2	107.9	0.8	14,3	70
Max	530397.3	8714716.55	1332.6	287.0	197.5	198.5	25.4	19,6	72

Variogram Modelling

Variogram modelling was used to assess the spatial continuity and variability of geometallurgical parameters. The spatial modelling module in Leapfrog Geo was used to build initial variogram parameters, which were then improved, depending on the data's features. A spheroidal variogram model was chosen because it effectively captures the anisotropic spatial continuity seen in mineral deposits. The final model parameters were a nugget effect of 0.1781, a total sill of 1.081, and a significant range of 200 m. This variogram model was consistently used in both the implicit and geostatistical estimation procedures, allowing spatial analysis findings to be readily compared across all datasets.

Implicit Modelling

The previously described variogram model was implemented in Leapfrog Geo, which was used in this work for both implicit and geostatistical estimates, as well as block modelling. The software was chosen because it provides a good implementation of the FastRBF for implicit modelling, alongside classic geostatistical methods such as OK, allowing for a uniform methodological comparison. The drillhole data entered into Leapfrog Geo contained collar coordinates, survey data (azimuth and dip), assay data, and geometallurgical parameters. During the import procedure, the software automatically detected possible issues such as anomalies in collar depth, missing intervals, and mismatched Hole ID values. Any discovered faults were addressed inside the software to assure the accuracy of future modelling. Data that could not be changed were removed to ensure data integrity. Assay and geometallurgical interval data were composited into 2 m intervals, which roughly matched the original mean sample length. Intervals less than this limit were discarded. A minimum interval coverage of 50% was used to address missing data and reduce possible compositing bias. Geometallurgical parameter estimation was performed using the implicit modelling method in Leapfrog Geo, using the variogram model mentioned before. The interpolation contained a drift component, with each parameter's mean value given correspondingly; for example, RQD's mean was 52.5%. An interpolant accuracy of 0.3 was used, and data values were clipped within set upper and lower ranges to reduce the possibility of overestimation or underestimation.

Geostatistical Method

Geostatistical methods were used in Leapfrog Geo to estimate geometallurgical parameters. The previously established variogram model was used, with parameters maintained consistently throughout both estimate methods to guarantee comparability. Negative estimated values were adjusted to zero to ensure geological validity. Leapfrog Geo automatically set discretisation with cell dimensions of X-5, Y-5, and Z-2, hence improving estimate accuracy inside the block model. Value clipping was used during interpolation, using predetermined minimum and maximum thresholds to restrict extreme estimations. The anisotropic ellipsoid parameters used in the OK process were synchronised with those applied in the implicit modelling workflow, guaranteeing uniform handling of spatial continuity in both methodologies. The final outputs included the estimated geometallurgical parameter values and their associated status indicators, used for further assessment and comparison.

Block modelling of Geometallurgical Data

To facilitate the evaluation of the estimated geometallurgical parameters, a three-dimensional block model was constructed in Leapfrog Geo, balancing computational efficiency with the size of the dataset. The model used a block size of 10 m × 10 m × 10 m, a measurement often chosen to correspond with practical factors like bench heights in open-pit mining or stope dimensions in underground mining. The block model was established at a reference position of (529843.20, 8714064.00, 1382.80), with dimensions of 640 m along the X-axis, 680 m along the Y-axis, and 350 m along the Z-axis. The implicit method and geostatistical methods estimators were used on this block model to get comparative estimates of the geometallurgical parameters. The use of a common block model framework guaranteed that any discrepancies noted between the two methods were due to the estimating methodologies, not to variances in model geometry or resolution.

RESULTS

Comparison of Block Models of Total Cobalt Generated through Implicit and Geostatistical Methods

The statistical analysis of the TCo estimations generated by the implicit and geostatistical methods indicated variations in central tendency, variability, and dispersion (Table II). The geostatistical method yielded a mean TCo of 1.04%. It also had a higher standard deviation and variability, indicating a broader range of anticipated grades within the model. This trend was further shown by a bigger coefficient of variation, underscoring increased relative dispersion of TCo values. The implicit method produced the highest individual TCo estimate at 8.78%, surpassing the maximum value of 6.92% achieved by the geostatistical method. These results underscore the significant disparities in how each method represents grade variability and extreme values inside the block model.

Table II. Statistical comparison between Implicit and Geostatistical methods for the TCo-based block models

Name	Implicit TCo (%)	Geostatistical TCo (%)
Block Count	6 416	6 416
Volume	6 416 000 m ³	6 416 000 m ³
Mean	0.99	1.04
Standard deviation	0.71	0.85
Coefficient of variation	0.71	0.81
Variance	0.49	0.72
Minimum	0	-0.02
Median	0.79	0.76
Maximum	8.79	6.92

Swath plots were used to compare TCo estimates derived from the geostatistical (blue) and implicit (red) methodologies (Figure 1). The geostatistical method exhibited increased variability, characterised by a broader spectrum of TCo values and more significant peaks and troughs across the model. The implicit method yielded a slower trend, marked by a consistent rise in TCo values interspersed with sporadic declines. In low-grade zones (Swath Numbers 0–20 and 50–60), both methodologies exhibited a generally similar pattern. However, the geostatistical method demonstrated more localised variations. In high-grade areas (Swath Numbers 20–50), the geostatistical method yielded more pronounced amplitude responses and deeper troughs, whereas the implicit method attenuated these fluctuations, resulting in a more uniform grade profile. The geostatistical method demonstrated more sensitivity to local spatial structure and data connection, whilst the implicit method offered a more comprehensive and generalised perspective on grade distribution.

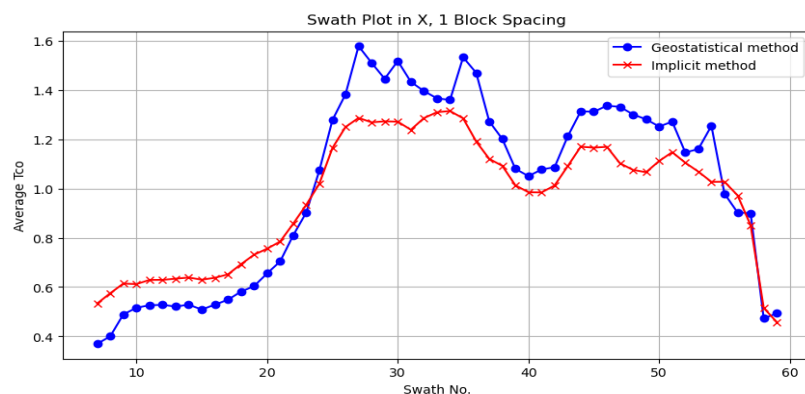


Figure 1. Comparison of swath plots between implicit and geostatistical methods for the TCo-based block models

Figures 2a and 2b illustrate the geographical distribution of TCo) throughout the two geometallurgical block models. Both models exhibit comparable proportions of high- and medium-grade TCo; however, they significantly diverge in local variability and spatial continuity. The implicit model (Figure 2a) has increased total TCo variability, characterised by more gradual transitions across the deposit. The geostatistical model (Figure 2b) generates more defined grade boundaries, especially in the middle area of the model, where significant transitions between high- and moderate-grade zones are apparent. The implicit method is well-suited for deposits exhibiting gradual geological variability, providing a

continuous depiction of mineralisation patterns. The geostatistical method, in comparison, delineates localised grade variations more clearly, which may be significant in deposits with intricate geological formations.

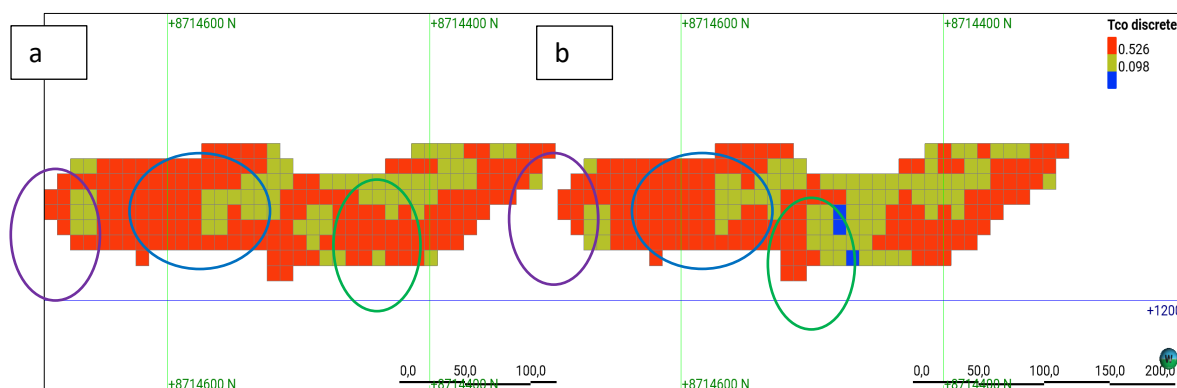


Figure 2. Visual comparison between a) Implicit method and b) Geostatistical method for the TCo-based block models.

Comparison of Block Models of Bond work Index Generated through Implicit and Geostatistical Methods

The statistical comparison of BWI estimations generated by the implicit and geostatistical methods indicates slight discrepancies in central values, accompanied by some variance in distribution features (Table III). The implicit method yielded a mean BWI of 12.79 kWh/t, somewhat lower than the 12.82 kWh/t mean obtained by the geostatistical method. The standard deviation for the implicit method was 2.02 kWh/t, slightly above the 1.95 kWh/t recorded for the geostatistical method, indicating somewhat more uncertainty in the implicit estimator. The coefficient of variation for the implicit method (0.16) was somewhat greater than that of the geostatistical method (0.15), indicating a relatively broader dispersion of BWI values. The implicit method yielded a lower minimum BWI of 6.49 kWh/t, in comparison to 7.00 kWh/t obtained by the geostatistical method. Although both methodologies generated comparable mean estimates, the geostatistical method demonstrated somewhat greater consistency, exhibiting less variability and a more confined range of values. The noted discrepancies probably indicate the responsiveness of each method to localised modifications in the dataset.

Table III. Statistical comparison between Implicit and Geostatistical methods for the BWI-based block models

Name	Implicit BWI (kWh/t)	Geostatistical BWI (kWh/t)
Block Count	6 416	6 416
Volume	6 416 000 m ³	6 416 000 m ³
Mean	12.79 kWh/t	12.82 kWh/t
Standard deviation	2.02 kWh/t	1.95 kWh/t
Coefficient of variation	0.16 kWh/t	0.15 kWh/t
Variance	4.09 kWh/t	3.78 kWh/t
Minimum	6.49 kWh/t	7 kWh/t
Median	13.16 kWh/t	13.17 kWh/t
Maximum	19.97 kWh/t	19.42 kWh/t

The swath plot compares the geostatistical and implicit methods in estimating the average BWI along the X-axis (Figure 3). Both methods display regional differences, with the geostatistical method producing a smoother and more stable profile in certain sections of the model. The implicit method shows minor discrepancies, particularly around local peaks and troughs, where small fluctuations are more apparent. Despite these differences, the two methods produced consistent results at the overall model scale, with limited variation in key areas. The comparison indicates that both methods are suitable for modelling BWI at a general scale, though differences in handling localised variations remain evident, especially when representing finer-scale features of the deposit.

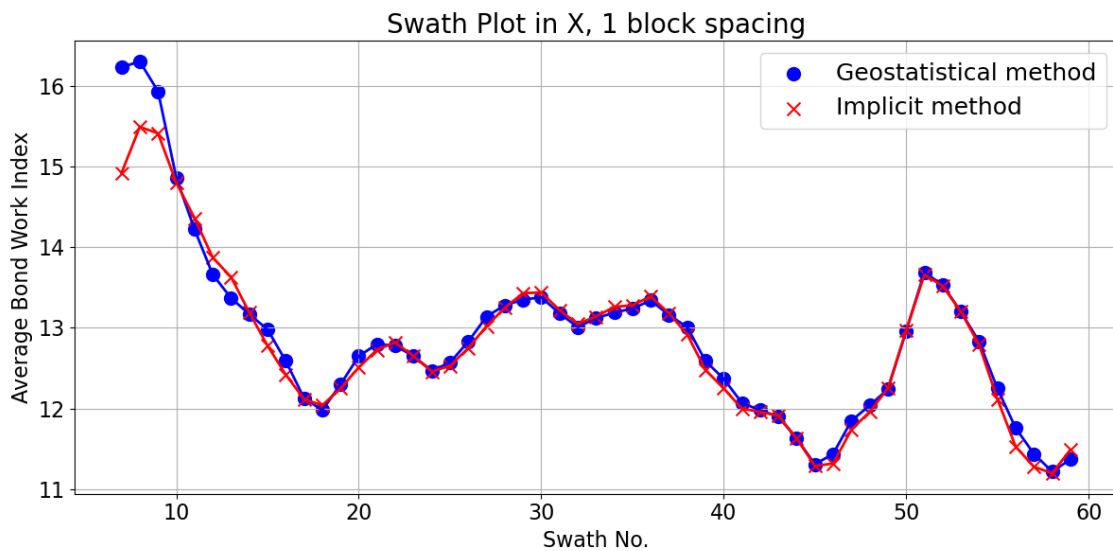


Figure 3. Comparison of swath plots between Implicit and Geostatistical methods for the BWI-based block models.

Figures 4a and 4b compare BWI estimates generated using the implicit and geostatistical methods within the geometallurgical block model. Both models display a broadly consistent pattern, with widespread intermediate BWI values (yellow), centred around approximately 13.2 kWh/t. Localised differences appear in areas of higher (blue) and lower (red) BWI values. The two methods differ in their representation of spatial continuity and the distribution of hardness values. The implicit model (Figure 4a) shows more fragmented zones of high BWI (blue), particularly on the left and central portions of the section. The geostatistical model (Figure 4b) produces more continuous zones of both high and low BWI, with sharper transitions between different BWI classes. These variations in model behaviour may reflect differences in how each method handles local estimation and spatial smoothing. Such differences can influence mine planning and energy optimisation. Variations in estimated rock hardness affect decisions related to grinding circuit design, energy forecasting, and throughput expectations.

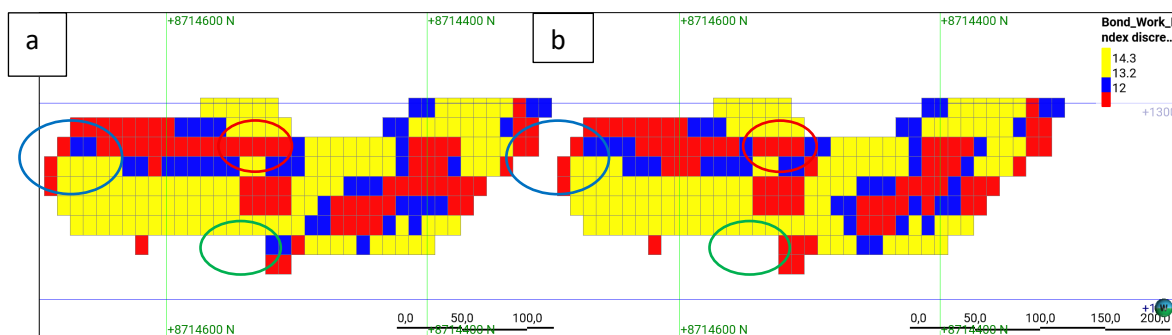


Figure 4. Visual comparison between a) Implicit method and b) Geostatistical method for the BWI-based block models.

Comparison of Block Model for Rock Quality Designation Index Generated through Implicit and Geostatistical Methods

Statistical analysis of the RQD block model, comparing the implicit and geostatistical methods, shows that the geostatistical method produces a slightly higher mean RQD value. This is accompanied by a standard deviation of 10.41% and a variance of 100.81%. The geostatistical model also exhibits reduced variability around the mean compared to the implicit model. Its minimum estimated RQD is 15.03%, and the maximum reaches 75.85%. The results indicate that the geostatistical method produces a more uniform distribution of RQD values, with a narrower range of estimates across the model.

Table IV. Statistical comparison between Implicit and Geostatistical methods for the RQD-based block models

Name	Implicit RQD (%)	Geostatistical RQD (%)
Block Count	6 416	6 416
Volume	6 416 000 m ³	6 416 000 m ³
Mean	56.49%	56.62%
Standard deviation	10.41 %	10.04 %
Coefficient of variation	0.18 %	0.18 %
Variance	108.43 %	100.81 %
Minimum	15.03 %	16.99 %
Median	56.52 %	56.52 %
Maximum	75.85 %	71.31 %

The swath plot in Figure 5 shows that average RQD values estimated by the geostatistical method range from 50.03% to 60.63%, while those produced by the implicit method range from 48.53% to 58.56%. In some swath intervals, the two methods produce closely aligned RQD values, indicating similar results in those areas. In other intervals, the differences between the methods are more pronounced. At Swath Number 13, for example, the geostatistical method produced an average RQD of 59.29%, compared with 58.54% from the implicit method. At Swath Number 47, the geostatistical estimate was 55.91%, while the implicit method produced 56.38%. These differences reflect local variations in how each method models the spatial continuity of RQD within the block model.

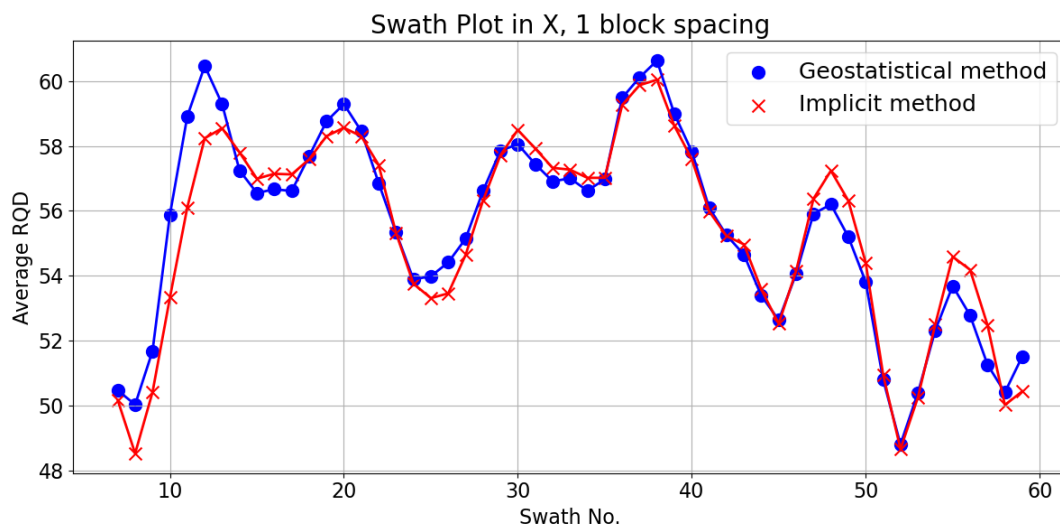


Figure 5. Comparison of swath plots between Implicit and Geostatistical methods for the RQD-based block models.

Figures 6a and 6b compares implicit modelling (Figure 6a) and geostatistical methods (Figure 6b) for the estimation of RQ within the geometallurgical block model. Both models exhibit similar overall spatial patterns, with dominant trends in the central high-RQD zone (red). Differences emerge in how the two methods represent spatial continuity and local variability. The implicit model shows more gradual transitions across the deposit, while the geostatistical model displays more pronounced oscillations in RQD values. A region marked with a black circle highlight one such difference. The implicit model predicts more fragmented zones with frequent extremes in RQD values, whereas the geostatistical model produces a smoother and more continuous representation of spatial variability. Such differences can influence how each method supports geotechnical interpretations and informs mine planning decisions.

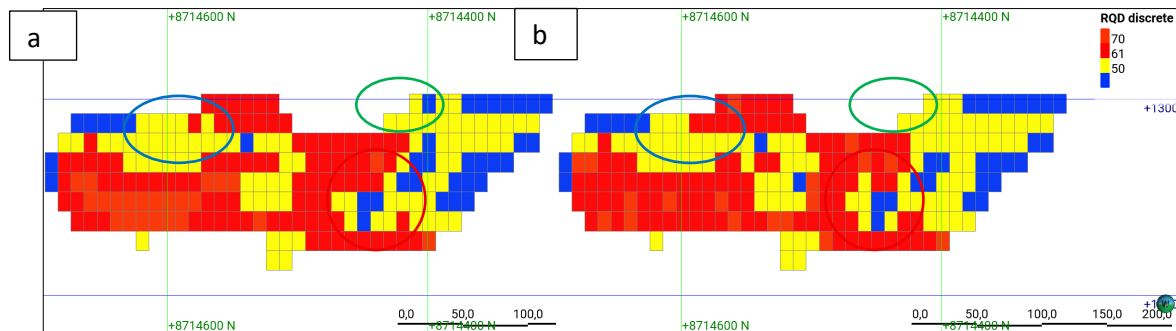


Figure 6. Visual comparison between a) Implicit method and b) Geostatistical method for the RQD-based block models.

Grade-Tonnage Curve for Implicit and Geostatistical Methods

The grade-tonnage curve illustrates the relationship between estimated ore tonnage and grade across varying cut-off grades. It provides insight into the quantity and quality of material that could be extracted under different economic scenarios. Figure 7 compares the grade-tonnage results obtained using the implicit and geostatistical methods. At a cut-off grade of 0.5%, the implicit method estimates a total ore tonnage of 11.29 million tonnes (Mt), with an average grade of 1.12% and an estimated commodity recovery of 90.83%. In comparison, the geostatistical method estimates a slightly higher ore tonnage of 11.36 Mt, with a higher mean grade of 1.34%, while 90.50% of the contained metal remains unmined. While the curves produced by both methods are similar in overall shape, minor differences appear in the estimated grades and recoverable tonnages. These variations reflect differences in how each modelling method represents grade distribution across the deposit.

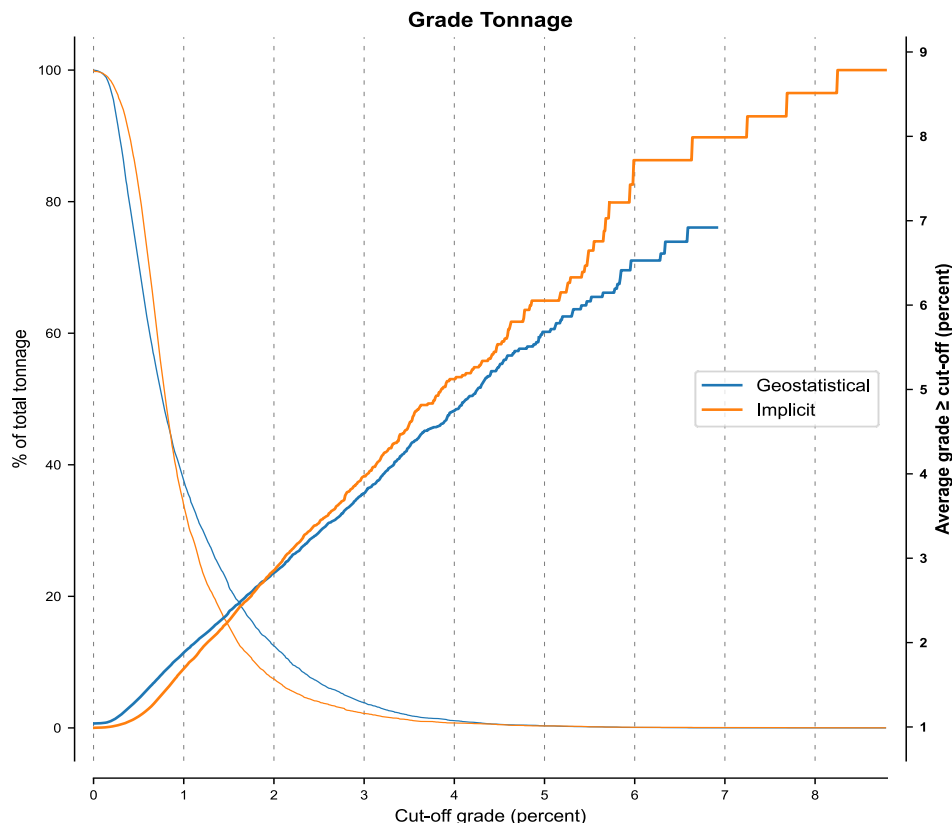


Figure 7. Comparison of grade tonnage curves generated using Implicit and Geostatistical methods.

Resource Estimation

The resource estimation results highlight differences between the implicit and geostatistical methods in the classification of ore, as well as in the estimated values of TCo, BWI, and RQD (Tables V and VI). The implicit method classified 253,000 cubic metres of high-grade ore, with an average grade of 3.04% TCo, a BWI of 13.83 kWh/t, and an RQD of 54.37%. The geostatistical method identified a smaller volume of 142,000 cubic metres of high-grade ore, but with a higher average grade of 3.78% TCo, a BWI of 14.04 kWh/t, and an RQD of 52.35%. For medium-grade material, the implicit model is estimated to be 2,147,000 cubic metres, with average values of 1.39% TCo, 13.02 kWh/t BWI, and 56.75% RQD. The geostatistical model produced a medium-grade volume of 2,049,000 cubic metres, with a higher average TCo of 1.72% a comparable BWI of 13.12 kWh/t, and an RQD of 56.89%. In the low-grade category, the implicit method assigned 2,145,000 cubic metres, with average values of 0.77% TCo, 12.70 kWh/t BWI, and 57.71% RQD.

The geostatistical method classified 3,101,000 cubic metres as low grade, with an average TCo of 0.71%, a BWI of 12.68 kWh/t, and an RQD of 57.07%. The two methods also differed in their estimation of waste material. The geostatistical model identified 1,124,000 cubic metres of waste, compared to 1,871,000 cubic metres in the implicit model. Waste exhibited similar average BWI and RQD values in both models, though the higher waste tonnage estimated by the implicit model may affect dilution considerations during mine planning. Across the entire resource model, the geostatistical method produced a higher overall mean TCo (1.05%) compared to the implicit model (0.99%). Mean BWI values were nearly identical: 12.82 kWh/t (geostatistical) and 12.79 kWh/t (implicit). Mean RQD values were also very close, at 56.62% for the geostatistical model and 56.49% for the implicit model. These variations in classification and estimated values are likely to influence mine planning decisions, particularly regarding processing circuit design and the management of operational risks associated with ore hardness and rock quality.

Table V. Resource estimation using Implicit method

				Average Value		
Class	Volume	Density	Mass	TCo	Bond_Work_Index	RQD
	m ³	g/cm ³	t	%	kWh/t	%
High	253 000.00	2.7	683 100.00	3.04	13.83	54.37
Low	2 145 000.00	2.7	5 791 500.00	0.77	12.7	57.71
Medium	2 147 000.00	2.7	5 796 900.00	1.39	13.02	56.75
Waste	1 871 000.00	2.7	5 051 700.00	0.51	12.5	55.07
Total	6 416 000.00	2.7	17 323 200.00	0.99	12.79	56.49

Table VI. Resource estimation using the Geostatistical method

				Average Value		
Class	Volume	Density	Mass	TCo	Bond_Work_Index	RQD
	m ³	g/cm ³	t	%	kWh/t	%
High	142 000.00	2.7	383 400.00	3.78	14.04	52.35
Medium	2 049 000.00	2.7	5 532 300.00	1.72	13.12	56.89
Low	3 101 000.00	2.7	8 372 700.00	0.71	12.68	57.07
Waste	1 124 000.00	2.7	3 034 800.00	0.37	12.52	55.43
Total	6 416 000.00	2.7	17 323 200.00	1.05	12.82	56.62

DISCUSSION AND CONCLUSION

In addition to evaluating technical performance, this paper examined the potential economic implications of using implicit modelling and geostatistical methods to estimate TCo, BWI and RQD in a geometallurgical block model. The results show that the geostatistical method produced slightly higher mean TCo values and captured more localised high-grade zones. This supports its use in selective mining and short-term production planning. The implicit method produced a smoother spatial profile. This makes it better suited to early-stage project evaluation and understanding broader mineralisation trends. For BWI, both methods provided similar mean estimates. The implicit model, however, showed greater variability. This could affect comminution circuit design and energy forecasts. RQD estimates were closely aligned across both models. The geostatistical method demonstrated lower variability, improving its ability to capture rock mass quality variations.

These modelling differences can influence key economic outcomes. Variations in high-grade ore estimation affect projected revenue and guide cut-off grade optimisation, which impacts project net present value. The broader distribution of BWI values in the implicit model introduces more uncertainty in energy consumption. This could influence grinding circuit sizing and operating costs. Differences in waste classification also affect mine scheduling and ore dilution, with downstream effects on processing efficiency and economic returns. A more conservative waste estimate from the geostatistical model may improve net smelter return by reducing dilution. The broader classification in the implicit model may provide greater flexibility in production planning but could introduce risk if marginal material underperforms. Choosing a modelling method should align with the project stage and economic priorities. Geostatistical modelling may be better suited to feasibility studies and investment decisions,

where detailed estimation of grade variability and processing parameters is required. Implicit modelling, with its smoother spatial trends, is valuable in exploration and conceptual resource studies focused on identifying broader patterns and development opportunities.

Both methods offer distinct advantages. Combining the local precision of geostatistics with the continuity modelling of implicit methods could provide balanced solutions for a range of mining applications. Further research should focus on developing such hybrid frameworks. While this study concentrated on comparative modelling behaviour and practical implications, a detailed error analysis was beyond its scope. Future work should incorporate such analyses to strengthen understanding of model accuracy and precision. Method performance should also be evaluated across different geological settings and larger datasets. Improving the quality of geometallurgical block models supports better resource estimation, risk management, and economic decision-making. Aligning the modelling approach with geological context, data quality, and project objectives is critical to achieving sound technical and financial outcomes. This study compared one implicit modelling technique (FastRBF) and one geostatistical method (OK). The findings reflect the performance of these specific approaches and should not be generalised to all methods within each category. Future work could expand this comparison by including additional techniques to further inform method selection.

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