SYDNEY, AUSTRALIA
2 — 4 SEPTEMBER 2024

INTERNATIONAL FUTURE MINING CONFERENCE 2024

Conference Proceedings

INTERNATIONAL FUTURE MINING CONFERENCE 2024

2–4 SEPTEMBER 2024
SYDNEY, AUSTRALIA

The Australasian Institute of Mining and Metallurgy
Publication Series No 6/2024

Published by:
The Australasian Institute of Mining and Metallurgy
Ground Floor, 204 Lygon Street, Carlton Victoria 3053, Australia

All papers published in this volume were peer reviewed before publication.

ISBN 978-1-922395-31-3

ORGANISING COMMITTEE

Serkan Saydam
FAusIMM
Conference Organising Committee Chair

Chengguo Zhang
MAusIMM

Peter Knights
MAusIMM

Steven Schafrik

Emily Sarver

Philipp Hartlieb

Clare Sykes

Burcin Ozturk

Carlos Tapia

Elisabeth Clausen

Bruce Fulton

Michelle Keegan

Burkhard Seifert

Rahman Daiya

AUSIMM

Julie Allen
Head of Events

Kathryn Laslett
Manager, Events

Raha Karimi
Program Manager, Events

REVIEWERS

We would like to thank the following people for their contribution towards enhancing the quality of the papers included in this volume:

Sela Akdag

Daisuke Asahina

Seher Ata

Ghislain Bournival

Elisabeth Clausen

Rahman Daiyan

Lorena Duranthon

Bruce Fulton

Bekir Genc

Philipp Hartlieb

Michelle Keegan

Mehmet Kizil

Peter Knights
MAusIMM

Binghao Li

Lily Li

Rudrajit Mitra

Claudia Mueller

Burcin Ozturk

Simit Raval

Emily Sarver

Serkan Saydam
FAusIMM

Steven Schafrik

Burkhard Seifert

Clare Sykes

Carlos Tapia

Chengguo Zhang
MAusIMM

FOREWORD

We are thrilled to have curated a pioneering program for the Sixth International Future Mining Conference, which is set to shape the next era of mining. This year's conference themes centre on innovation, mining in extreme environments and unconventional deposits, sustainable practices, energy innovations, and the evaluation of future skills and workforces—all while navigating the intersection of technological advancements and environmental responsibilities.

Mining production plays a critical role in global socio-economic development, forming an integral part of nearly every industrial value chain. However, the sustained demand for minerals globally, combined with the challenge of deeper orebodies, declining ore grades, and extreme environmental conditions, presents a series of obstacles for the future of the industry. These challenges are further compounded by social and environmental pressures. To address these complexities, this conference will provide a platform for discussion, aimed at enabling the minerals industry to incorporate scientific knowledge and advanced technologies from diverse disciplines. Our goal is to guide the sector towards maintaining cost-effective, safe, and environmentally responsible operations.

Collaboration across industry sectors is key to ensuring that innovation is implemented in ways that meet the long-term needs of the mining sector. This conference will bring together executives, experts in operations, researchers, technologists, government representatives, and stakeholders, all of whom play vital roles in shaping strategic and technologically sound futures for mining.

This conference builds on the success of the past events held in Sydney in 2008, 2011, 2015, 2019 and 2024. The Future Mining Conference Series has become a distinguished event within the mining industry, offering a unique platform for communication and collaboration among present and future leaders, technologists, scientists, engineers, mine executives, investors, academics, government representatives, and all other key stakeholders. The series serves as a forum for exploring innovations and the transfer of technological advancements from other sectors into mining. It also provides a stage for examining future human skill needs, operational trends, and 'blue-sky' scenarios for the future of mining, including strategies for education, novel systems, and new resource directions.

Key themes this year include sustainable mining, emission reduction and low carbon economy, mining in extreme environments and unconventional deposits, mining internet of things, data visualisation and artificial intelligence, technology integration, future skills and workforce evolution,

We are proud to feature six distinguished keynote speakers: Maki Ikeda (Head of Product Development, BHP Think and Act Differently), Danielle Martin (Co-Chief Operating Officer and Director of Social Performance, ICMM), Dr Hemant Chaurasia (Chief Product Officer, Fleet Space Technologies), Professor Julien Epps (Dean, UNSW Engineering), Dr Luke Sollitt (Branch Chief Planetary Systems, NASA Ames Research Centre), and Rajkumar Mathiravedu (Chief Technical Officer/Chief Operating Officer, Orica Digital Solutions). Together, they will offer diverse perspectives on the future of mining.

All extended abstracts and papers in this conference have undergone rigorous independent peer review to ensure the highest standards of relevance and quality.

We extend our sincere thanks to all who contributed to making this event possible. Special gratitude goes to the authors and presenters for their invaluable work, the organising committee for their dedication, and our sponsors and exhibitors for their support in ensuring the success of the conference.

Organising such an event requires considerable effort, experience, and enthusiasm. We would like to acknowledge the team from The Australasian Institute of Mining and Metallurgy (AusIMM) for their tireless and professional work in making this event a reality.

On behalf of the organising committee, The University of New South Wales (UNSW Sydney), and AusIMM, we warmly welcome you to the Sixth International Future Mining Conference 2024.

Yours faithfully,

Professor Serkan Saydam *FAusIMM*

Future Mining Conference Organising Committee Chair

SPONSORS

Major Conference Sponsor

Platinum Sponsors

Automation Sponsor

Gold Sponsors

Technical Session Sponsor

Dinner Sponsor

Welcome Reception Sponsor

CORICA MINING SERVICES

Note Pad and Pens Sponsor

DIGITAL MINING SOLUTIONS

Name Badge and Lanyard Sponsor

ORICA

Conference Supporter

AROSE

Australian Remote Operations for Space and Earth

CONTENTS

Energy innovations

Future skills and workforce evolution

Innovations

Mining in extreme environments and unconventional deposits

Sustainable mining

Energy innovations

An assessment of battery trolley systems' performance in surface mines

H Bao[1], P Knights[2], M Kizil[3] and M Nehring[4]

1. PhD Candidate, The University of Queensland, St Lucia Qld 4072. Email: h.bao@uq.edu.au
2. Professor, The University of Queensland, St Lucia Qld 4072. Email: p.knights@uq.edu.au
3. Associate Professor, The University of Queensland, St Lucia Qld 4072.
   Email: m.kizil@uq.edu.au
4. Senior Lecture, The University of Queensland, St Lucia Qld 4072. Email: m.nehring@uq.edu.au

ABSTRACT

The mining sector, a notably energy-intensive industry worldwide, is a major consumer of fossil fuels, leading to significant carbon emissions globally. The move towards electrification, coupled with advancements in battery technology, has redirected focus from traditional diesel-powered solutions to battery-powered alternatives. This paper introduces a novel mining haulage system, termed the Battery Trolley system, and examines its theoretical foundations, configurations, and operational processes. It offers a comprehensive analysis of the system's characteristics and limitations. Through a hypothetical road simulation, the study analyses various battery mining trucks, calculating energy consumption based on force parameters and tailoring battery sizes to contemporary materials and technology. When assessing various battery truck alternatives—considering aspects such as battery size, effective payload, duty cycle, energy efficiency, productivity, and single-shift production—a range of performance outcomes and characters become apparent within the mining context. The findings indicate that Battery Trolley configurations, requiring smaller battery capacities, entail lesser compromises on effective payload. Consequently, these configurations achieve a higher duty cycle, reduced energy consumption per tonne, heightened productivity, and enhanced single-shift production capabilities compared to Battery-only alternatives. The comparative analysis of Battery Trolley with stationary charging (BT-S) and Battery Trolley – dynamic charging (BT-D) underlines that battery Trolley systems are capable of overcoming the challenges associated with battery size, thus successfully fulfilling the production demands of large truck applications in mining. This positions Battery Trolley systems as a more advantageous option for the decarbonisation of mining fleets, underscoring their potential in contributing to the sector's sustainable evolution.

INTRODUCTION

There is now global consensus on the urgency of decarbonisation efforts (Plazas-Niño, Ortiz-Pimiento and Montes-Páez, 2022). Achieving the emissions reduction benchmarks established by international governments necessitates the introduction of innovative technological interventions for substantive decarbonisation. Particularly in the mining sector—a field characterised by high energy consumption predominantly from fossil fuels—the adoption of clean, renewable energy technologies, alongside cost-efficient, low-emission alternatives, becomes crucial. Transitioning towards electrification of mining equipment represents a viable strategy for maintaining competitive edge while phasing out high-emission systems. The evolution of electrification and battery technologies offers a pathway for the gradual replacement of diesel-powered mining machinery and vehicles with electricity-powered and energy storage solutions. Such a transformation indicates a shift towards an 'all-electric' mining operation, placing increased focus on electricity generation and battery storage capabilities (Zuliani, Guilbaud and Carreau, 2021).

The Mining Haulage Trucks (MHTs) is identified as a significant source of carbon dioxide (CO_2) emissions in surface mining operations (Li *et al*, 2021). These operations predominantly utilise large MHTs equipped with diesel-electric propulsion systems for the transportation of ore or waste from the mine pit's loading sites to dump sites at higher elevations (Feng and Dong, 2020). Trolley Assist systems, a technology well-established in the mining industry, are currently employed by several Original Equipment Manufacturers (OEMs) including Komatsu, Caterpillar, Hitachi, and ABB. Battery Trolley systems represent the start of a shift towards electrification, aiming to establish the mining industry's first zero-emission truck fleet. The realisation of the Battery Trolley systems concept hinges on the integration of battery-electric drivetrains, autonomy, Trolley Assist, and energy recovery system (ERS) technologies. This integration is pivotal in steering the mining industry towards a more sustainable and environmentally friendly future.

This research introduces the concept of Battery Trolley systems and assesses their technical viability. Three Battery Trolley system configurations: dynamic charging; stationary charging; and dual trolley Battery Trolley systems are available for decision-makers to choose from, each with its own advantages and disadvantages (Bao *et al*, 2023a). It also compares these configurations based on mining system-level considerations to assess their future potential. The evaluated configurations include Diesel-Electric Truck (DET), Trolley Assist Truck (TAT), Battery-only Truck (BOT), Battery Trolley with dynamic charging truck (BT-D), and Battery Trolley with stationary charging truck (BT-S). The energy consumption calculation method and battery size design theory for battery mining trucks are studied based on a hypothetical mining scenario (Bao *et al*, 2024). Furthermore, a mining case is designed for comparison battery alternatives' performance in terms of battery size, effective payload, energy efficiency, productivity, and overall production within a single shift leveraging mining haulage simulation software.

BATTERY TROLLEY SYSTEMS

Battery Trolley systems represent an integration of technologies, encompassing a battery-electric drivetrain, autonomy, trolley assist, and ERS. These systems offer a suite of configurations tailored to the unique conditions and technological integrations of each mining site. Decision-makers are presented with three distinct Battery Trolley system configurations from which to select: Battery Trolley with dynamic charging, Battery Trolley with stationary charging, and Battery Trolley with dual trolley systems. Each configuration comes with its own set of benefits and drawbacks, necessitating a thorough analysis to determine the most appropriate solution based on site-specific requirements and operational goals. This diversified approach allows for a more customised and efficient adoption of electric truck technology in mining operations, aligning with the industry's move towards sustainability and reduced carbon emissions.

The mining industry is working towards achieving zero-emissions fleet requirements and the deployment of Battery Trolley systems is one option to achieve this goal. Several OEMs such as Komatsu, Caterpillar, Hitachi, and ABB are researching and developing battery-trolley operation on top of their existing Trolley Assist systems that are already being used in the industry. Battery Trolley is designed to offer an emission-free haulage mining system that utilises the full source of electrical power through autonomous high-intensity battery-electric trucks, Trolley Assist systems, and ERS. Figure 1 illustrates the conceptual operation of Battery Trolley systems on the trolley ramp.

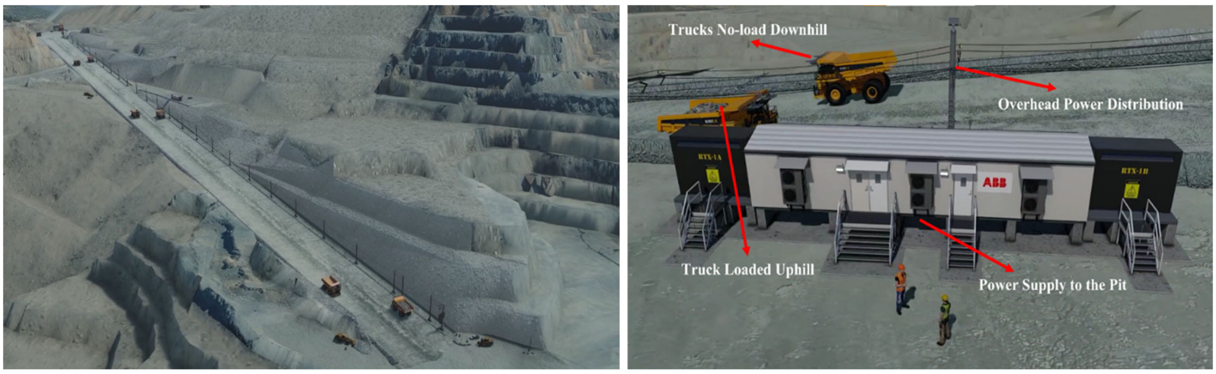


FIG 1 – The diagram of Battery Trolley systems on the trolley ramp (ABB, 2024).

Battery trolley system's configurations

The configuration design is based in mining system theory, aimed at supporting the extensive adoption and implementation of Battery Trolley technology within surface mining haulage systems. Initially, the study depicts the deployment prerequisites, operational mechanisms, and power sources associated with diverse Battery Trolley configurations. Subsequently, it emphasises that mining decision-makers must carefully evaluate the compatibility of various Battery Trolley set-ups in terms of benefits and drawbacks, taking into account the distinctive characteristics of each mine site. This comparative assessment is critical for ensuring that the chosen technology aligns with site-specific requirements, thereby facilitating an optimised transition to more sustainable and efficient haulage operations.

Dynamic charging battery trolley system

Dynamic charging technology allows grid power to be used to power the electric drive motors and simultaneously charge the onboard truck battery. In dynamic charging Battery Trolley systems, the onboard battery can receive enough charging electricity from the uphill grid charging and the downhill energy recovery to balance energy consumption in one haul cycle. The dynamic charging Battery Trolley consists of the battery-electric truck, the Trolley Assist system, and dynamic charging technology.

Figure 2 illustrates the operational process and power source of the dynamic charging Battery Trolley systems. The battery-electric trucks load and haul using battery power, and switch to trolley mode when they reach the trolley ramp. During this time, energy is consumed at a lower rate for cooling and idling while the grid power is used to simultaneously charge the onboard battery and power the wheel motors. Once the battery-electric truck reaches an ex-pit flat road, it returns to battery power mode to complete hauling, queueing, dumping, and returning manoeuvres. On the downhill ramp, the ERS converts the truck's braking power into electric energy that can be stored on the battery, allowing the truck to reuse battery power for the return journey to the loading point.

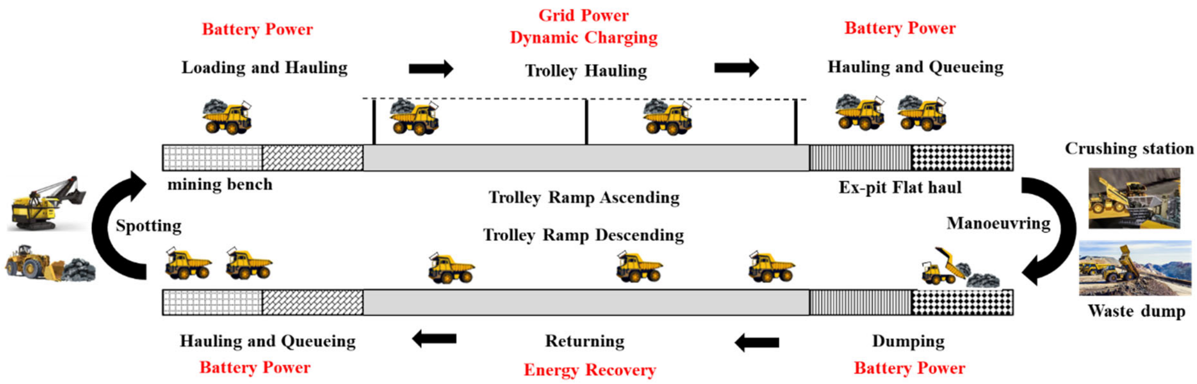


FIG 2 – A schematic of dynamic charging Battery Trolley systems operational process and power source (Bao *et al*, 2023b).

Stationary charging battery trolley system

Stationary charging requires a battery station for battery charging or battery swapping. The choice between charging and swapping methods depends on the charging C-rate (a measure of the rate at which a battery is discharged relative to its maximum capacity) (Power Sonic, 2024) and swapping time. The battery station is located on the crest of the pit to provide ample permanent space for infrastructure and truck parking. The stationary charging Battery Trolley system consists of a battery-electric truck, Trolley Assist systems, and the battery station.

Figure 3 depicts the operational process and power source of the stationary charging Battery Trolley systems. Battery-electric trucks operate using battery power for loading and hauling, switching to trolley mode when they reach the trolley ramp. The energy consumption of the on-board battery significantly decreases because it just needs to provide energy for cooling and idling. Meanwhile, the grid power can provide maximum power to the wheel motors, enabling the truck to operate at a faster speed on the trolley ramp. Upon reaching the ex-pit flat road, the truck switches back to battery power mode to complete hauling, queueing, dumping, and returning manoeuvres. The battery-electric truck requires battery charging or swapping at battery station within several cycles, depending on the on-board battery size and energy consumption profile. On the downhill ramp, the truck enters energy recovery mode, converting its braking power into electricity that is stored in the battery. The truck then uses the stored energy to return to the loading point.

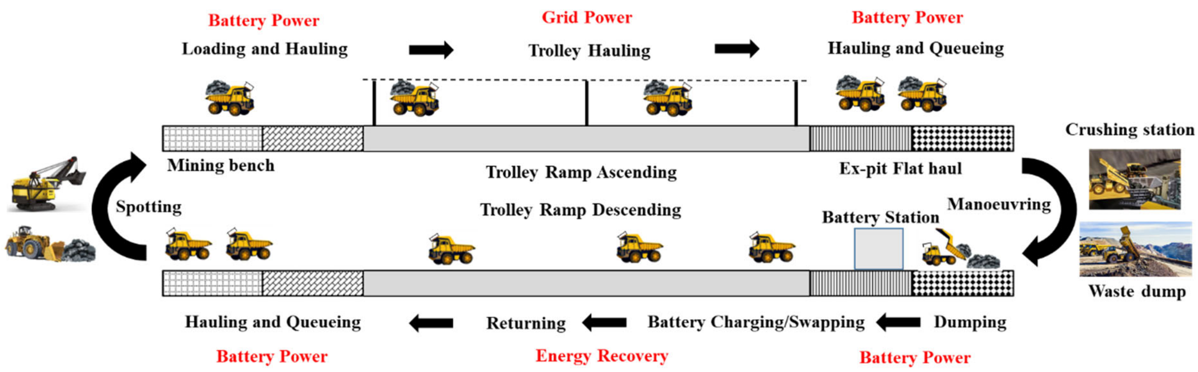


FIG 3 – A schematic of stationary charging Battery Trolley systems operational process and Power Source (Bao *et al*, 2023b).

Dual charging battery trolley system

Research indicates that for downhill hauls, a bidirectional substation facilitates energy feedback to the grid (Mazumdar, 2011). A dual trolley system can be installed for improved energy capture performance in a Battery Trolley system. The uphill ramp trolley allows for grid power to be utilised to power the electric drive motors, while the downhill ramp trolley captures the braking energy and returns it to the grid. The dual trolley Battery Trolley comprises battery-electric trucks, double trolley systems, and a battery station. An alternative to a dual trolley system is to apply an onboard ERS to feed energy back into the battery (Terblanche, Kearney and Knights, 2018).

Figure 4 depicts the operational process and power source of the dual trolley Battery Trolley system. The battery-electric trucks load and haul using battery power, and switch to trolley mode when they reach the trolley ramp. During this time, the energy is consumed at a much lower rate for cooling and idling. Meanwhile, the grid power can provide maximum output power to the wheel motors, allowing the truck to operate at a faster speed on the trolley ramp. Upon reaching the ex-pit flat road, the truck returns to battery power mode to complete hauling, queuing, and dumping manoeuvres. The battery-electric truck requires battery charging or swapping at battery station within each cycle or every two or three cycles, depending on the on-board battery size and energy consumption. The truck then enters energy recovery mode downhill by engaging the trolley line, which captures braking energy and returns it to the grid. The truck then reuses battery power to return to the loading point.

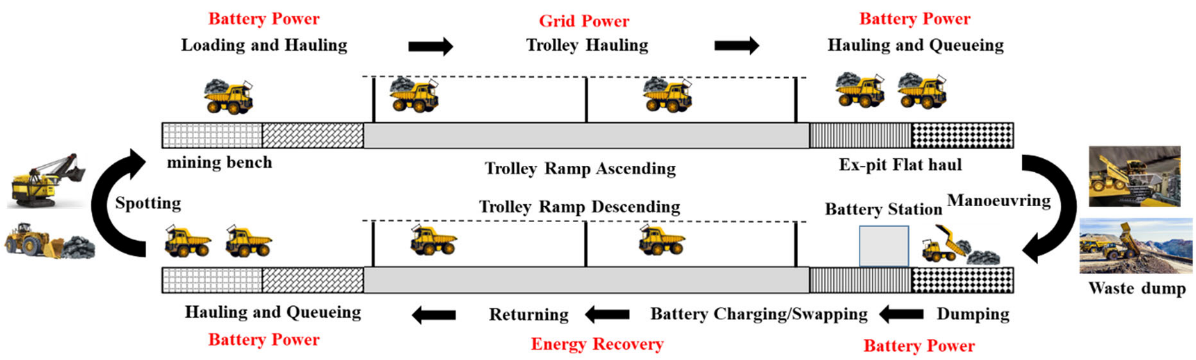


FIG 4 – A schematic of dual trolley Battery Trolley systems operational process and power source (Bao *et al*, 2023b).

Battery trolley system's characteristics

To date (2024), Battery Trolley is a conceptual mining system that has not been widely retrofitted and tested by original equipment manufacturers and several mining companies. Without extensive practical experience with the Battery Trolley, it is difficult to accurately determine its pros and cons. However, conclusions can be drawn about its advantages and disadvantages by comparing it with conventional truck-shovel systems, In-Pit Crushing and Conveying (IPCC), and Trolley Assist systems.

Advantage and disadvantage

The Battery Trolley offers a green solution to achieve the first zero-emissions truck fleet in mining haulage systems by using battery-electric power instead of relying on fossil fuels. An analysis (Terblanche, Kearney and Knights, 2018) of the energy consumption profile of mining haul trucks indicates that about 70 per cent to 80 per cent of energy is consumed on the uphill ramp, where the Battery Trolley system provides grid power to the battery-electric trucks. In addition, the Battery Trolley addresses the challenge of battery size faced by the mining industry compared to existing battery-electric vehicles. The relatively long-standing trolley services provide opportunistic charging when in contact with the trolleys over selected sections of the mine with permanent roadways, eliminating or delaying battery swaps during normal shifts. The Battery Trolley also leads to lower maintenance and energy costs for a single truck as it does not have a diesel engine and electricity is relatively cheaper. Over the entire mine operating life, the Battery Trolley incurs lower operating costs compared to conventional diesel truck fleets due to its use of electricity as end-use energy, similar to IPCC.

Despite the benefits of the Battery Trolley, there are still several technical challenges associated with its use. Transitioning from diesel-electric to battery-electric power can significantly increase electricity costs and demand for the mine, as well as the capital expenditures for power infrastructure and battery stations. To operate a battery-electric load and haul fleet, mine design must be altered to allow for battery stations and related equipment, and some haul routes may need to be modified compared to a conventional diesel fleet (Leonida, 2020). Another limitation is reduced flexibility, as current fleets do not require semi- or permanent infrastructure, making them difficult to move as mining operations progress. Mine scheduling and planning must accommodate downtime for electrical lines and support extensions and relocations. In addition, the road surface must be level for the pantograph to stay in contact with the overhead wires, resulting in higher maintenance for the trolley ramps (Halim *et al*, 2022). The Battery Trolley fleet also faces challenges such as battery size and performance, high upfront capital costs, system capacity and availability, truck fleet dispatching, restrictions in mine design, and maintenance schedule arrangements for ancillary equipment. Other options of charging, such as dynamic charging, inductive, or other advancing technologies, may become more prevalent, in addition to battery swapping or charging (Global Mining Guidelines Group, 2022).

Capacity limitation

One of the challenges of using Battery Trolley systems is their capacity and productivity since several trucks rely on trolley lines (Mazumdar, 2011). Despite the performance improvements offered by Battery Trolley systems, they can be offset by trolley power limitations and the time needed for charging or swapping batteries. To determine if Battery Trolley systems can meet mining production requirements, it is recommended to study the system's overall productivity from both dynamic charging and stationary charging perspectives. This will help decision-makers in the mining industry tailor proper production scheduling.

The truck operation follows a discrete event and the truck scheduling follows a uniform distribution during one haul road time under the optimum truck dispatching scenario. The dynamic charging adoption results in the distribution of the trolley power (8 MW) between the electric wheel motors (3500 kW) and the charging on-board battery packages (4500 kW), allowing only one truck to enter the trolley ramp at a time. The trolley ramp speed during dynamic charging is limited to 20 km/h, lower than the maximum speed of 27 km/h, to allow for more time to charge the battery-electric truck by engaging the trolley line. This slows the truck speed, but increases the charging of electricity for the battery packages to meet the energy needs for the entire cycle.

Overall, the trolley system cannot accommodate two trucks at the same time. Hence, trolley power is the most critical factor that limits the productivity of the Battery Trolley. To study the maximum productivity of the working face bench, it is assumed that multiple fleets carry out material transportation along the same haul route. The equation for calculating the number of fleets in the dynamic charging condition is presented below:

$$\frac{\frac{Trolley\ Length}{Ramp\ Speed}}{Haul\ Cycle\ Time} \times Number\ of\ Trucks\ per\ Fleet \times Number\ of\ Fleets \leq 1 \quad (1)$$

Due to the adoption of stationary charging, the trolley power of 8 MW can support two trucks, allowing for a maximum output power of 4000 kW for the electric wheel motors. As a result, two trucks can operate simultaneously on the same trolley ramp. The equation for calculating the number of fleets in the stationary charging condition is presented below:

$$\frac{\frac{Trolley\ Length}{Ramp\ Speed}}{Haul\ Cycle\ Time} \times Number\ of\ Trucks\ per\ Fleet \times Number\ of\ Fleets \leq 2 \quad (2)$$

As previously explained, the trolley power limits the number of trucks that can be engaged on the trolley line simultaneously. However, the electric motor output power on the trolley is another parameter that influences the Battery Trolley capacity. The equation for calculating the maximum number of trolley trucks is:

$$N_{mt} = \left\lfloor \frac{P_t}{P_{emo} + B * P_{dc}} \right\rfloor \quad (3)$$

Where:

N_{mt}: Maximum number of trolley trucks, is the maximum number of trucks capable of engaging the trolley grid simultaneously due to trolley power limitations.

P_t: Trolley power, is the power which the rectifier substation is able to provide for the trolley grid. It is the maximum power capacity for a Battery Trolley system to engage battery-electric trucks, kW.

P_{emo}: Electric motor output power on Trolley, is the power that battery-electric truck's electric motor output on the trolley ramp. The electric motor output power is the direct factor that influences truck speed. In this study case, P_{emo} is 3500 kW and the corresponding ramp speed is 20 km/h in the dynamic charging adoption while P_{emo} is 4000 kW and the corresponding ramp speed is 27 km/h in the stationary charging counterpart, kW.

B: Boolean variable, represents 0 or 1 value. In the dynamic charging Battery Trolley system, B equals 1 while B equals 0 in the stationary charging counterpart.

P_{dc}: Dynamic charging power on the trolley, is the power the trolley line provides to recharge the on-board battery when the battery-electric truck engages the trolley line.

According to the calculation equation for the maximum number of trolley truck, the final number of fleets we can get from the equation.

$$\frac{\frac{Trolley\ Length}{Ramp\ Speed}}{Haul\ Cycle\ Time} \times Number\ of\ Trucks\ per\ Fleet \times Number\ of\ Fleets \leq Maximum\ Number\ of\ Trolley\ Trucks \quad (4)$$

The results indicate that:

1. Trolley power limitations significantly affect the capacity of Battery Trolley systems.
2. A stationary charging option can achieve higher capacity and productivity than dynamic charging.

ENERGY CONSUMPTION AND BATTERY SIZE

While the transition to battery technology in mining equipment offers promising emissions reduction possibilities, there are several unique characteristics and challenges specific to mining applications that require careful investigation. One crucial consideration is the significant disparity in energy density between diesel fuel and state-of-the-art lithium batteries used in current mining applications. Diesel fuel has a much higher heating value of approximately 12 000 Wh/kg, whereas the specific energy of lithium batteries for mining applications currently stands at around 150 Wh/kg (Ritter, Elbert and Onder, 2016). Even if taking into account tank-to-wheel efficiency, combustion engine-based systems have a much higher specific energy compared to electric powertrains (Ertugrul *et al*, 2020). Hence, there is a need for research on battery sizing specifically tailored to mining battery electric alternatives, considering the dedicated mining haul routes. Currently, the battery constitutes a significant portion of the capital cost, and appropriately sizing the battery for mining haulage applications can enhance the cost-effectiveness of mining systems (Shaobo *et al*, 2021).

Haul road simulation

Surface mining contributes to the extraction of approximately two-thirds of the world's industrial metals (Kalantari, Sasmito and Ghoreishi-Madiseh, 2021). During actual mining operations, a mining truck follows a specific sequence: it is loaded with ore or waste material at the loading location, ascends to the designed point area to dump the material, and then descends back to the loading site without any load. These trucks predominantly operate off-road within a mine, repeatedly undergoing cycles of repeated speed, mine load and climbing/descending (Valenzuela Cruzat and Valenzuela, 2018).

Haul road profiles

A typical hypothetical mining haul road was constructed for further simulation and comparison (Figure 5). The study focuses on the Komatsu 830E truck with a payload capacity of 220 t. The total haulage distance is 8660 m, and there is an elevation of 314.4 m from the working face to the dumping face. The haul ramp has a gradient of 8 per cent, while the haul flat section has a gradient of 0 per cent. It is important to note that the green section in the figure represents the long haul ramp or trolley ramp. In the DET and BOT conditions, there are two long haul roads, each with a length of 800 m, while in the TAT and BTT conditions, there are two trolley ramps. Each trolley ramp consists of two segments, both 400 m long. Each segment is powered via a dedicated substation. Additionally, there is a 25 m flat road before the long trolley ramp to allow the truck to accelerate and reach the required approach speed. Figure 3 displays more profiles of the haul road, showing the relationships between gradient, load state, rolling resistance coefficient, and elevation with road distance. The green dashed line represents the trolley haul road condition, which has a rolling resistance coefficient of 1.5 per cent to ensure a good connection between the pantograph and trolley lines, while the conventional haul road has a rolling resistance coefficient of 2.5 per cent.

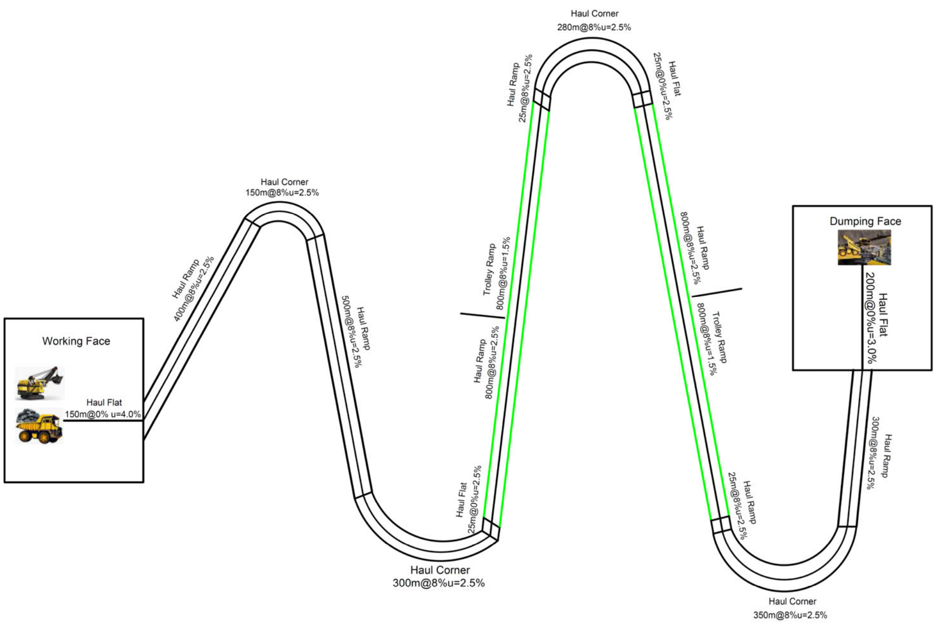


FIG 5 – Hypothetical mining haul road (Bao *et al*, 2024).

Haul cycle time performance

Figure 6 provides the trucks' operation time profiles, illustrating a comparison of cycle times for the five truck applications. The trucks' arrival sequence at the ramp crest is as follows: BT-S – 965 sec, BT-D – 1040 sec, TAT – 1121 sec, BOT – 1139 sec, and DET – 1377 sec. This sequence is determined by the fact that BT-S achieves the highest speed on the haul ramp, while DET exhibits the slowest speed during the haulage period. In terms of completing one cycle, the sequence is as follows: BT-D – 1817 sec, TAT – 1947 sec, DET – 2204 sec, BT-S – 2342 sec, and BOT – 2500 sec. This order is influenced by the battery swapping process required for BT-S and BOT at the crest of the pit. These findings indicate that BT-S has the shortest arrival time at the ramp crest due to its fast speed, while BT-D exhibits the shortest cycle time overall. TAT and DET follow with slightly longer cycle times, and finally, BOT has the longest cycle time due to the battery swapping process.

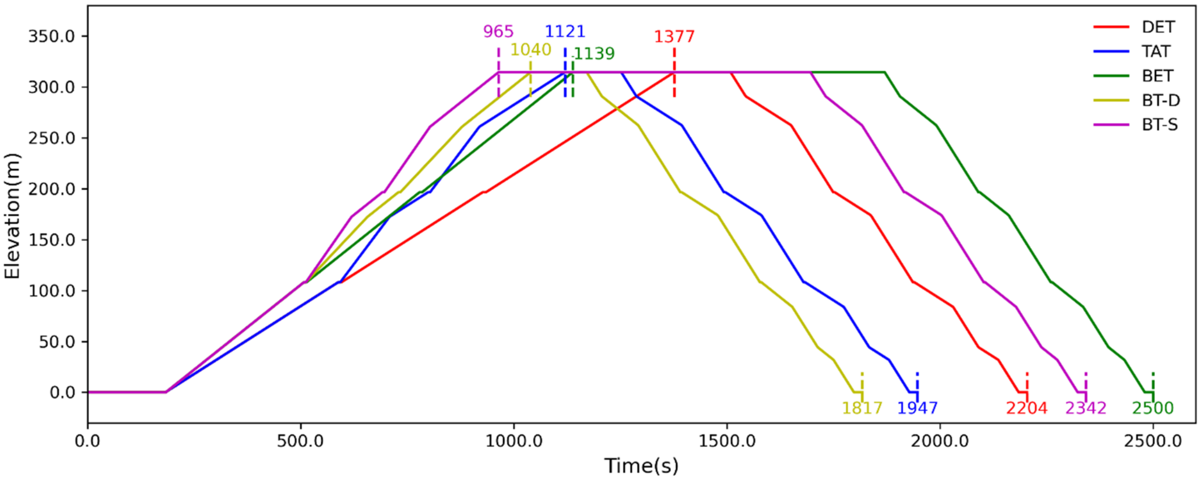


FIG 6 – Truck cycle time of all applications (Bao *et al*, 2024).

Energy calculation

The energy consumption of MHT is affected by various parameters, with equipment characteristics and operating conditions being the most significant factors. These parameters play a crucial role in determining the overall energy usage of MHT during their operations (Awuah-Offei, 2018). This research applied a consistent base truck configuration and utilised the same haul road profile, which is a part of the operating conditions. Additionally, an important aspect of the operating conditions is the force parameters that the trucks experience on the road. These force parameters have a significant impact on the energy consumption of the trucks (Figure 7).

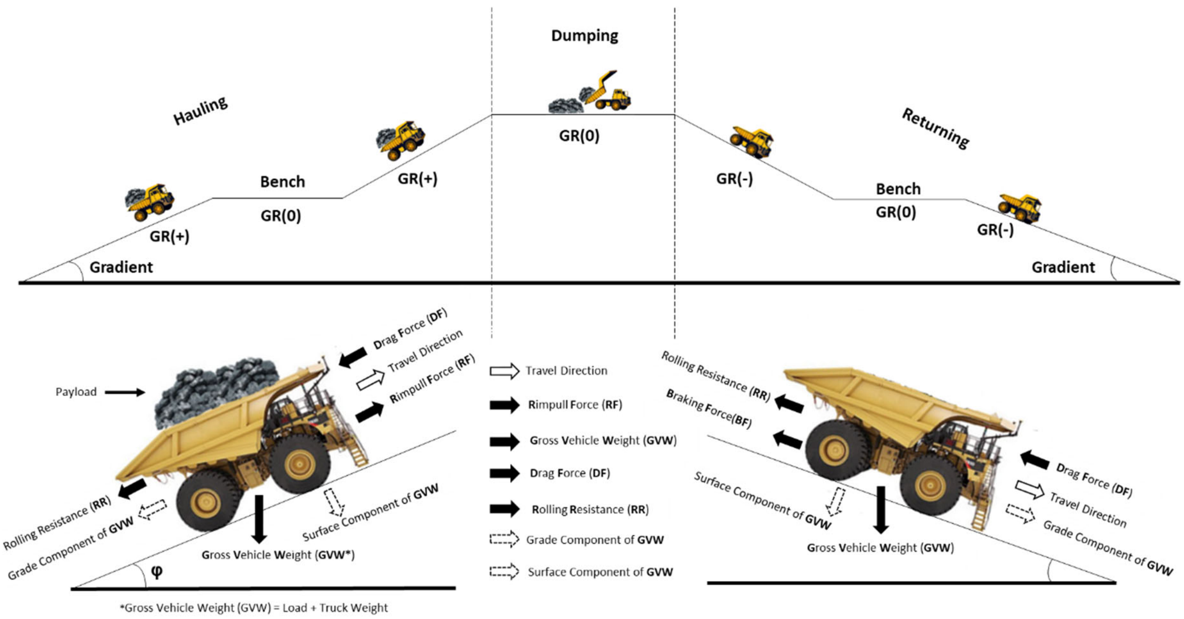
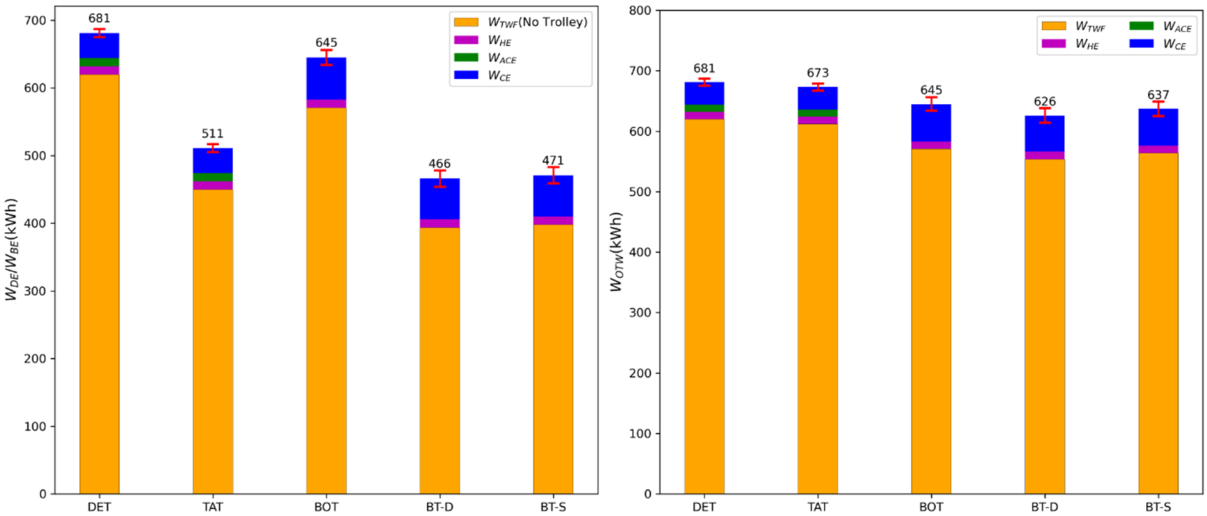


FIG 7 – Force parameters of MHT (Bao *et al*, 2024).

The primary contributors to energy consumption, including total work of force (W_{TWF}) and auxiliary energy (W_{AE}), are the on-board energy sources such as the diesel tank and battery packages.

Figure 8a illustrates the components of on-board energy consumption, including diesel energy (W_{DE}) and battery energy (W_{BE}). Trolley power proves effective in reducing the amount of on-board energy that needs to be carried. Although hydraulic energy (W_{HE}), air conditioner energy (W_{ACE}), and cooling energy (W_{CE}) constitute small portions of the total energy consumption, they still consume a significant amount of on-board energy, particularly W_{CE} in battery applications. In Figure 8b, the overall total energy (W_{OTW}) consumption for each application is presented. The results indicate that manual diesel-electric trucks have the highest energy consumption (681 kW/h), while automatic battery trolley dynamic trucks have the lowest energy consumption (626 kW/h). According to this study, the total energy gap between the different alternatives is less than 7 per cent. However, if the study considers a higher proportion of trolley ramps and incorporates the impact of battery size and engine specifications, the gap between diesel trucks and battery alternatives may widen.



(a) On-board W_{DE}/W_{BE} energy consumption (b) W_{OTW} energy consumption

FIG 8 – Energy consumption comparison of W_{DE}/W_{BE} and W_{OTW} (Bao *et al*, 2024).

Battery size design

Battery material selection

Lithium-Ion Batteries (LIBs) have become the dominant choice for various energy storage applications, primarily due to their longer lifespan and higher energy density compared to other battery types (Feng and Dong, 2022). Among the different types of LIBs, $LiFePO_4$ (LFP) has gained widespread adoption in heavy-duty transportation, including MHT. This is because LFP offers advantages such as lower cost, lower toxicity, well-established performance characteristics, excellent long-term stability, and suitability for a wider range of temperature variations. Given the heavy usage of MHT, the cycle life-span (number of cycles until 80 per cent of the initial capacity remains) becomes crucial in determining the frequency of battery replacements.

Based on the characteristics of LFP batteries, along with the parameters of the selected battery packages, the discharging range for these MHT applications is set to be between 20 per cent and 95 per cent to ensure battery health (Moore, 2022). The estimated battery lifespan is based on the number of cycles required for the cell chemistries to reach 80 per cent of their initial capacity, taking into account a battery life degradation of 20 per cent (Knibbe *et al*, 2022). Battery efficiency represents the overall efficiency from the tank to the end use, including both the tank-to-wheel and tank-to-auxiliary efficiencies. According to the findings of a previous study (Cunanan *et al*, 2021), the tank-to-wheel efficiency of a BEV is estimated to be around 68 per cent, with a range spanning from 64.4 per cent to 86 per cent. The losses in efficiency can be attributed to factors such as powertrain friction and electrical resistances encountered during the transmission of electricity. The battery efficiency is assumed to be 80 per cent in this study. The energy density of LFP is 150 Wh/kg. Additionally, the cost of LFP is \$240/kWh, while the cost of LTO is \$750/kWh (Knibbe *et al*, 2022).

Battery size calculation

The battery package design allows for a 25 per cent discharging range margin, 20 per cent battery degradation loss over the life and 20 per cent battery efficiency loss, which typically can account for 65 per cent of the battery 'nameplate' capacity. Note that the real usable capacity we can consume in normal MHT operation is merely 35 per cent of total capacity (Knibbe, 2022).

The reasonable battery mass (M_B) of BOT, BT-D and BT-S should be calculated based on above parameters, which are on-board battery energy per cycle (W_{BE}), cycle times per battery swapping (S_t), discharging range loss (L_{DR}), battery degradation loss (L_{BD}), battery efficiency loss (L_{BE}) and battery energy density (D_{BE}). The Equation 5 shows the battery size calculation method.

$$M_B = \left\lceil \frac{\left(\frac{W_{BE} \times S_t}{1 - L_{DR} - L_{BD} - L_{BE}}\right)}{D_{BE}} \right\rceil \quad (5)$$

A COMPARISON OF VARIOUS BATTERY TRUCK ALTERNATIVES

In the context of decarbonising fleet applications, the BOT configuration emerges as a significant alternative. This section aims to conduct a technical comparison between the battery-only application and the Battery Trolley system. The evaluation will cover several critical aspects: battery size, effective payload, duty cycle, energy efficiency, productivity, and overall production within a single shift. This comparison is essential for understanding the performance capabilities and limitations of various Battery Trolley systems in decarbonisation efforts.

Study case

Mining scenario

The simulation of haulage operations at the King Solomon gold mine, conducted using HAULSIM software RPMGlobal, serves as a case study highlighted in the provided screen capture (shown in Figure 9). The mine features a pit with multiple source locations, alongside several destinations including dumps, crushers, and stockpiles. Material will be moved from the source to the destinations by trucks on a road network. This network is designed to mirror the typical layout found in mining operations, utilising the 3D HAULSIM platform for realistic configuration. A specific route from Source 1 to Dump 1 has been chosen for the execution of the simulation study (shown in Figure 10).

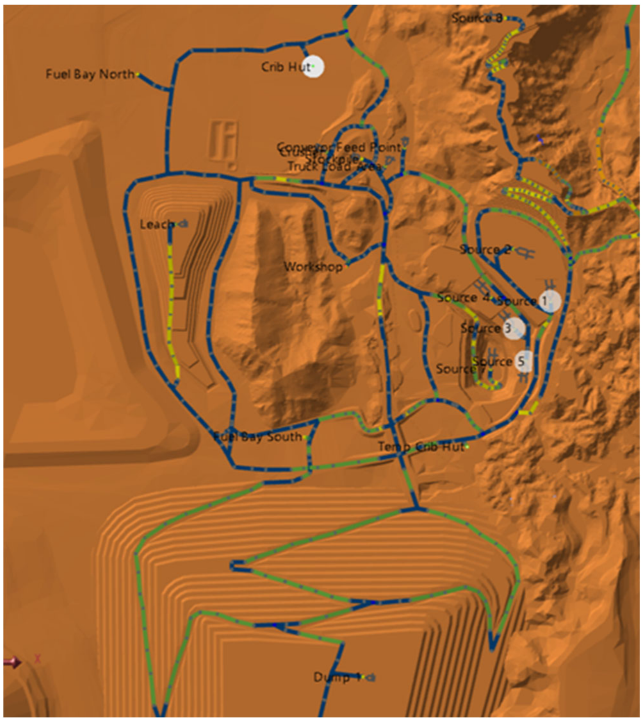


FIG 9 – The whole haulage system and road network.

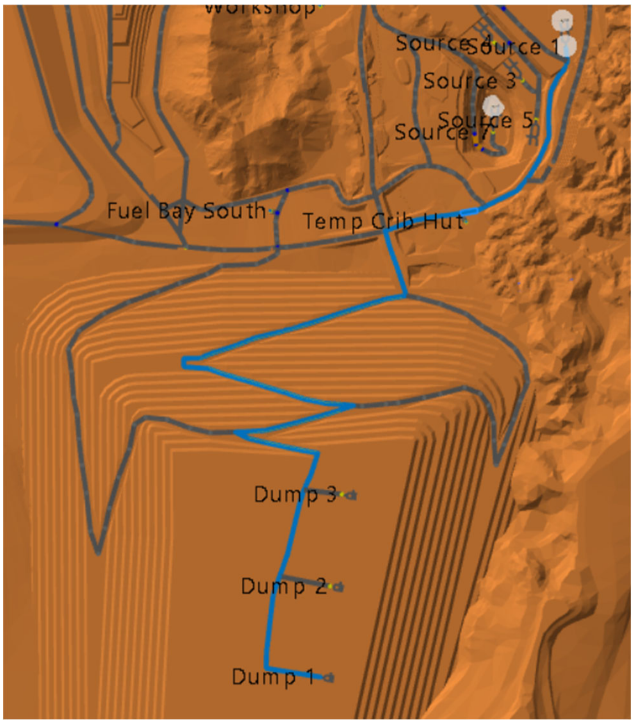


FIG 10 – Selected haulage route from source 1 to dump 1.

HAULSIM integrates fleet assets, mining operational strategies, and personnel into a 'digital twin' of any mining operation, offering a precise depiction of haulage operations across various mine sites. At the heart of HAULSIM lies a 3D Discrete Event Simulation (DES) engine, making it a pivotal mining simulation software capable of quantifying the effects of modifications within haulage systems. The models generated by HAULSIM capture the intricate and dynamic characteristics of a mine site in full, including model variability, interactions, and dependencies within haulage systems. Due to HAULSIM's reliance on accurate data, users are empowered to explore numerous 'why' and 'what-if' scenarios, thereby understanding the potential impacts of adjustments to a mine's haulage system (RPMGlobal, 2024).

Mining system design

In this scenario, the Komatsu 830E serves as the focal point for a comparative study exploring different electrification strategies: BOT, BT-S, and BT-D configurations. The parameters for the Komatsu 830E, sourced from the HAULSIM equipment library, include a rated payload capacity (for waste) of 252.8 tons and the gross power of 1865 kW. The specifications for the battery-powered alternatives are formulated based on realistic assumptions. The BOT configuration is designed to operate along the same haul routes as its conventional diesel counterparts. Given the unique characteristics associated with trolley systems in uphill segments, this study specifically targets four uphill segments for the installation of trolley configurations, where the truck consumes the most on-board energy.

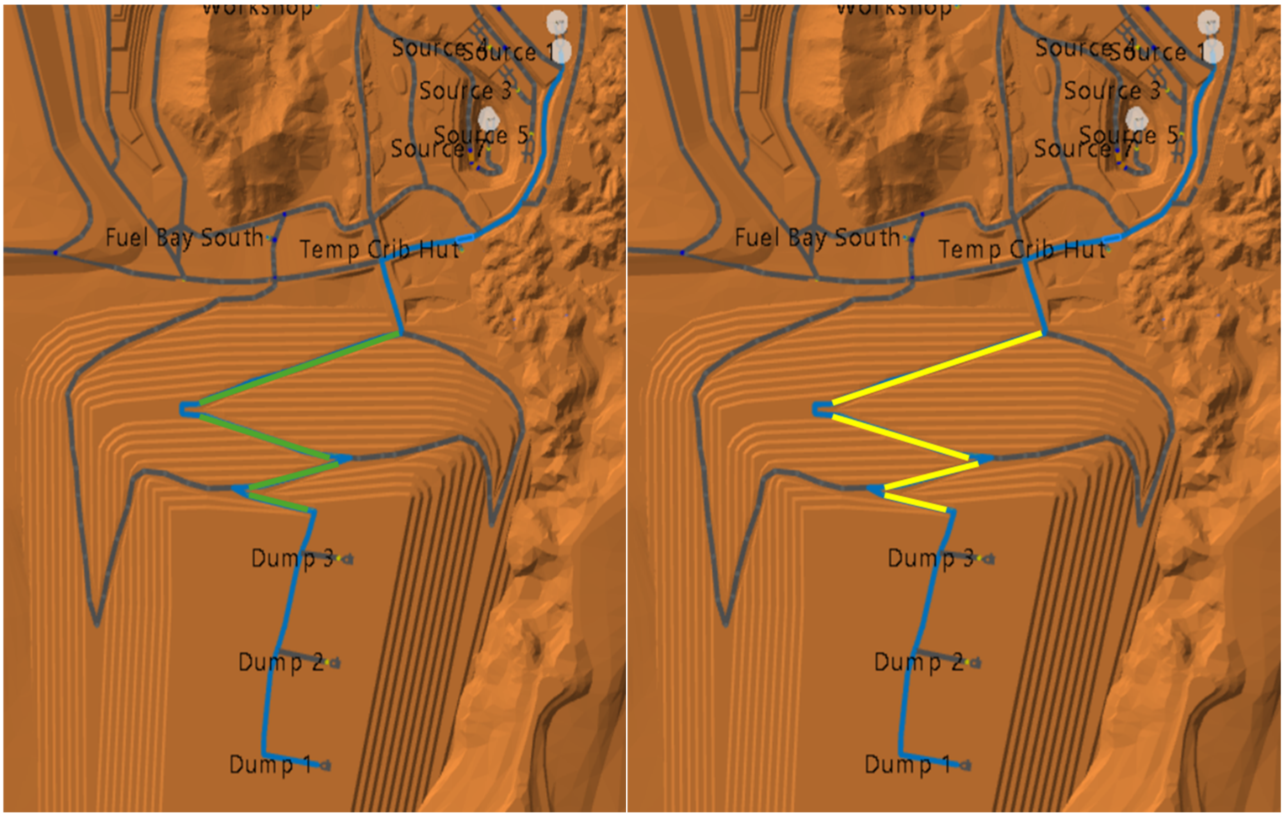


FIG 11 – The trolley ramp section in study case (the green sections are stationary charging design; the yellow sections are dynamic charging design).

In the context of operating battery-electric trucks within mining environments, the timing for swapping or charging the onboard battery emerges as a crucial factor. This is especially significant after a certain number of haul cycles when the battery capacity is out, as mine sites aim to deploy BOT and BT-S to fulfill mining production tasks. Unlike applications for passenger vehicles, the unique conditions of mine sites necessitate that the onboard battery's capacity is tailored to the specific demands of mining haul route cycles and production requirements. This case study delves into calculating the energy consumption and required onboard battery capacity for trucks under various scenarios: ranging from swapping or charging the battery after completing one to five haulage cycles. While the Battery Trolley system with dynamic charging eliminates the need for battery swapping, the onboard battery's size is still a critical consideration, determined by the number of haulage cycles it can support. This approach ensures that the design and operation of battery-electric trucks are optimised for the specific challenges and demands of mining operations.

Parameter assessment

Battery size

Utilising the aforementioned theoretical framework on energy consumption and battery sizing, this study proceeds to calculate the required battery size for BOT, BT-S, BT-D applications. The outcome is shown in Table 1.

TABLE 1
The battery size of various configurations.

Configurations	Battery mass (t)				
	One cycle	Two cycles	Three cycles	Four cycles	Five cycles
BOT	4.4	8.4	12.3	16.3	20.3
BT-S	1.9	3.4	4.8	6.3	7.7
BT-D	1.9	3.4	3.4	3.4	3.4

The BOT configuration necessitates the largest battery capacity among all these battery-electric truck applications, attributing its higher on-board battery energy requirement. With an increase in haulage cycle times, the BOT alternative requires progressively larger batteries to accommodate the heightened energy consumption demands. Conversely, the battery mass of the BT-S configuration is markedly less substantial than that of the BOT. This reduction is due to the significant electrical power supplied by the trolley system during uphill segments—where the BOT's onboard battery experiences its highest energy consumption—thus significantly decreasing the onboard battery size requirement for the BT-S application.

The BT-D shows a similar energy consumption profile across the haulage cycle with BT-S configuration. Nonetheless, the incorporation of dynamic charging technology enables the BT-D configuration to operate with a considerably smaller onboard battery. In theory, dynamic charging allows for the onboard battery to be recharged to full capacity while connected to the trolley system, suggesting that the battery size for BT-D could be optimised based on the energy demands of a single haulage cycle. However, for reasons of safety and reliability, this study proposes sizing the onboard battery for the BT-D configuration to meet the energy requirements of two haulage cycles, taking a more reasonable engineering approach to design.

Effective payload

Effective payload refers to the actual tonnage of material that a truck can transport in each haul cycle. In the context of battery-electric configurations – which encompass electric engines, battery packs encased in steel covers, ERS, pantographs, and other components – while simultaneously removing the internal combustion engine and diesel tank, it becomes imperative to recalculate the effective payload to account for these alterations. Given the centrality of battery size to this research and there are no available abovementioned parameters to evaluate, the study assumes that the mass of the battery is the sole variable impacting the real payload, as described in the provided Equation 6. This assumption allows for a focused analysis on how battery mass influences the truck's ability to carry material, highlighting the trade-off between energy storage capacity and payload efficiency in battery-electric truck configurations.

$$Effective\ Payload = Rated\ Payload - Battery\ Mass \tag{6}$$

According to battery size calculation and above equation, the effective payload outcome and visualisation is shown in Table 2 and Figure 12.

TABLE 2
The effective payload of various configurations.

Configurations	Effective payload (t)				
	One cycle	Two cycles	Three cycles	Four cycles	Five cycles
BOT	222.4	218.4	214.5	210.5	206.5
BT-S	224.9	223.5	222.0	220.6	219.1
BT-D	224.9	223.5	223.5	223.5	223.5

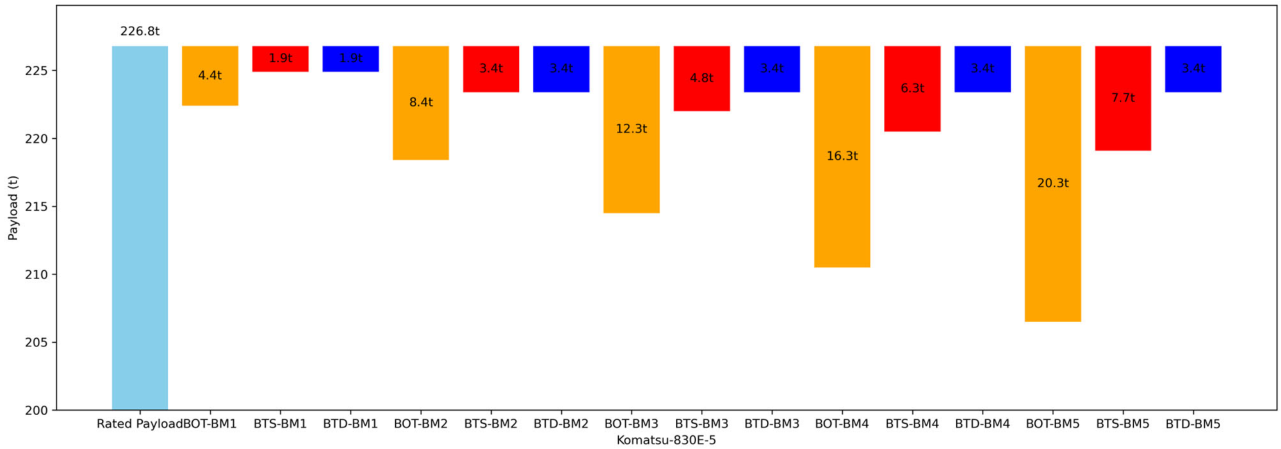


FIG 12 – The effective payload loss in various configurations.

The findings indicate that the BOT configuration exhibits the lowest effective payload, primarily due to its larger battery mass. As the number of haulage cycles increases, the loss in effective payload for the BT-S is significantly less when compared to the BOT configuration. Furthermore, the BT-D demonstrates the most favourable effective payload performance, with its advantage becoming especially evident as the number of haulage cycles increases. This pattern underscores the efficiency of dynamic charging technology in minimising the trade-off between battery mass and payload capacity, thereby enhancing the operational efficiency of BT-D configurations in prolonged haulage tasks.

Duty cycle

In the realm of battery electric vehicles (BEVs), the duty cycle metric is instrumental in evaluating the ratio of operational time to battery charging time. In this study, the duty cycle is the ratio of time that a battery truck is operating relative to the shift time. This research undertakes the calculation of the duty cycle metric across a range from one to five cycles for different battery applications within a single working shift, which spans 12 hrs. This approach provides a comprehensive understanding of how various battery configurations perform over multiple operational cycles, highlighting their efficiency and practicality in sustaining prolonged work periods without necessitating frequent recharges. This metric thus serves as a critical indicator of the operational viability and endurance of BEVs in real-world applications. The duty cycle outcome is shown in Table 3, and the battery swapping sequences of BOT and BT-S are visualised in Figure 13.

TABLE 3

The duty cycle of various configurations in one shift.

Configurations	Duty cycle (%)				
	One cycle	**Two cycles**	**Three cycles**	**Four cycles**	**Five cycles**
BOT	63%	78%	83%	89%	89%
BT-S	60%	75%	83%	86%	89%
BT-D	100%	100%	100%	100%	100%

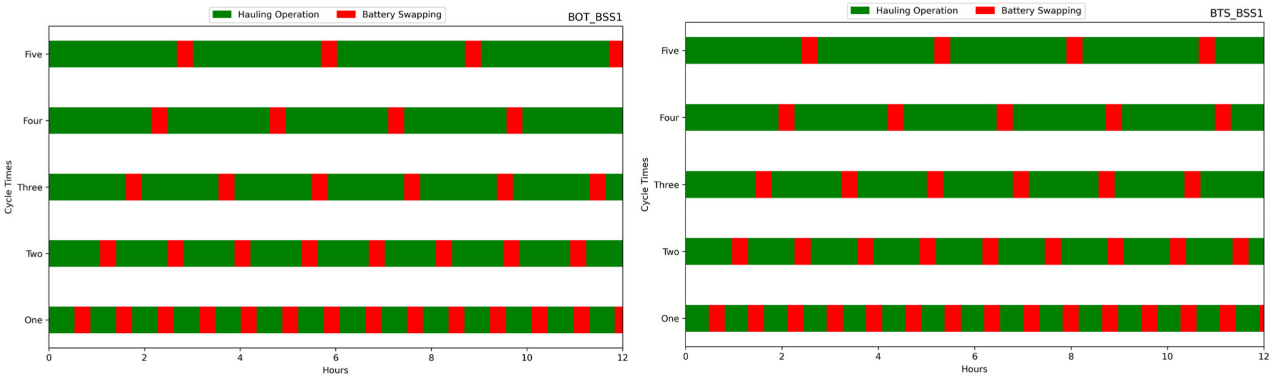


FIG 13 – Hauling operation and battery swapping sequence (left is BOT, right is BT-S).

The results reveal that as the cycle time extends, the duty cycle exhibits improved performance owing to the reduced necessity for battery swapping in both BOT and BT-S configurations. Specifically, as the frequency of required battery swapping decreases, the vehicles can operate for longer durations uninterruptedly, thereby enhancing the duty cycle metric. In scenarios of equal cycle time, the BT-S configuration typically demonstrates a lower duty cycle relative to the BOT. This is attributed to the BT-S's enhanced speed on uphill sections when connected to the trolley system, which facilitates quicker ascents and potentially reduces the overall cycle time. Conversely, BT-D achieves a duty cycle of 100 per cent within a single work shift. This optimal performance is due to the elimination of battery swapping operations, as the dynamic charging system allows the vehicle to be continuously charged or assisted during operation. This feature ensures that the BT-D can maintain constant operation throughout the work shift, underscoring the significant advantage of dynamic charging technology in optimising the operational efficiency of battery electric vehicles in mining applications.

Energy efficiency

In traditional haulage systems, energy efficiency, measured in kWh per kilometre (kWh/km), serves as a pivotal metric for evaluating the performance of BEVs. This measurement gauges the amount of energy consumed for each kilometre travelled. However, the layout of mine pits and haulage routes undergoes constant evolution as excavation progresses and the pit expands.

Given the dynamic changes inherent to mining environments, this study adopts a more tailored approach to assessing energy efficiency within the context of mining haulage systems. Instead of focusing solely on the distance travelled, the research emphasises the energy required to transport a tonne of material. This redefined metric, which quantifies the energy expenditure per tonne hauled, offers a more relevant and practical measure of energy efficiency for mining operations. It directly correlates energy usage to the core activity of material transport, providing a clearer insight into the operational efficiency of BEVs in a mining setting and their potential for optimising energy consumption against the backdrop of variable mining tasks and production requirements. The energy efficiency of various configurations is shown in Table 4.

TABLE 4

The energy efficiency of various configurations.

Configurations	Energy efficiency (kWh/t)				
	One cycle	Two cycles	Three cycles	Four cycles	Five cycles
BOT	1.61	1.64	1.67	1.70	1.73
BT-S	1.57	1.58	1.59	1.60	1.61
BT-D	1.57	1.58	1.58	1.58	1.58

A higher value of energy efficiency indicates a requirement for more energy to transport material per tonne. The findings can be articulated as follows:

- An increase in cycle time correlates with a rise in energy efficiency, interpreted here as higher energy consumption per tonne. This trend is attributable to the necessity for larger battery capacities to support extended operational durations, consequently elevating the energy required for material haulage.
- The BT-D configuration demonstrates the most favourable energy efficiency, characterised by its lower energy consumption per tonne. This efficiency is facilitated by the BT-D's ability to operate effectively with a considerably smaller on-board battery, thereby completing multiple haulage cycles with reduced energy expenditure. This capability not only underscores the advantage of dynamic charging technology but also highlights the BT-D's potential to significantly reduce the energy consumption associated with material transport in mining operations.

Productivity and production

The ultimate goal of the mine haulage system is to fulfill the production requirements outlined in short-term mine planning. Mining decision-makers are tasked with deploying potential decarbonisation fleets, making their choices based on the productivity and production capabilities of these fleets per shift. The productivity and production of various configurations is shown in Table 5.

TABLE 5

The productivity and production of various configurations.

Configurations	Productivity (t/h)				
	One cycle	Two cycles	Three cycles	Four cycles	Five cycles
BOT	255.9	311.0	331.5	340.0	342.8
BT-S	275.7	344.2	374.0	389.8	399.0
BT-D	466.2	463.1	463.1	463.1	463.1
	Production per shift (t)				
BOT	1919	2902	3315	3626	3656
BT-S	1994	3098	3740	4028	4256
BT-D	5594	5558	5558	5558	5558

The findings indicate that with longer cycle times, both BOT and BT-S configurations achieve greater productivity and production, benefitting from reduced battery swapping frequencies. Additionally, under similar cycle time conditions, BT-S outperforms BOT in productivity, attributed to its smaller onboard battery package. Significantly, the BT-D configuration demonstrates markedly superior productivity and production capabilities within a single shift owing to the 100 per cent duty cycle.

CONCLUSIONS

This study delves into the theory, configurations, and operational processes of Battery Trolley systems, providing an in-depth analysis of their characteristics and capacity constraints. Transitioning from diesel-electric to battery-electric trolley operations emerges as not only technically viable but also a critical advancement in the pursuit of decarbonisation, positioning battery-electric haulage as a sustainable solution. Each configuration of the Battery Trolley system brings distinct advantages and challenges. The study highlights that the power supply constraints inherent to trolley systems significantly influence their operational capacity. From the perspective of technology fleet management, the stationary charging option is recognised for its superior capacity benefits. Conversely, the dynamic charging approach is noted for eliminating the need for extensive battery station infrastructure and the operation of battery charging/swapping within the haul cycle, presenting a streamlined operational model.

This paper explores the application of single battery mining trucks through a hypothetical road simulation, analysing energy consumption based on force parameters and designing battery sizes with contemporary battery materials and technology. This approach serves as a technical basis for the broader adoption of battery-powered alternatives. The utilisation of trolley applications and ERS presents significant energy savings for MHT alternatives, with DET exhibiting the highest overall energy consumption and onboard energy per haul cycle. Conversely, BT-D configuration demonstrates the lowest energy consumption in a single cycle. The study also sheds light on battery utilisation, revealing that only 35 per cent of the battery's 'nameplate' capacity is effectively utilised, factoring in losses from discharging range (25 per cent), battery degradation (20 per cent), and battery efficiency (20 per cent). Based on these insights, a theory for battery size design was formulated to guide further case studies.

In evaluating various battery truck alternatives across parameters such as battery size, effective payload, duty cycle, energy efficiency, productivity, and single-shift production, disparate performance outcomes and characteristics emerge within the mining scenario. The BOT configuration demands the largest battery capacity to meet the energy requirements of a haul cycle, resulting in the greatest sacrifice in effective payload due to its larger battery size. This also leads to a lower duty cycle, higher energy consumption per tonne, reduced productivity, and diminished single-shift production. Moreover, these performance metrics will alter as the cycle time for battery swapping/charging increases due to the augmented battery size. Conversely, the BT-S exhibits improved performance across these metrics compared to BOT, with the BT-D showcasing the optimal performance. The BT-D requires the smallest battery size, achieves a 100 per cent duty cycle, exhibits lower energy consumption per tonne, and achieves higher productivity and single-shift production.

However, these analyses focus solely on single truck operations. When considering a large-scale deployment of the Battery Trolley system, the BT-D's capacity limits, reliability, and flexibility pose significant challenges compared to other alternatives. Overall, the comparative performance of BT-S and BT-D demonstrates that Battery Trolley systems can overcome to a certain extent the challenges associated with battery size and successfully meet mining production requirements in ultra-capacity truck applications, offering a more favourable alternative to decarbonisation mining fleet. A more detailed comparison, grounded in actual mine site practices from a mining system-level perspective, is essential to thoroughly evaluate the potential of Battery Trolley systems.

ACKNOWLEDGEMENTS

Authors appreciate the support provided by RPMGlobal for the use of HAULSIM.

REFERENCES

ABB, 2024. eMine™ Trolley System to meet Copper Mountain Mining's sustainable development goals in Canada, ABB Mining. Available from: <https://new.abb.com/mining/reference-stories/open-pit-mining/trolley-assist-solution-to-meet-copper-mountain-mining-sustainable-development-goals-in-canada> [Accessed: 1 October 2023].

Awuah-Offei, K (ed), 2018. *Energy Efficiency in the Minerals Industry – Best Practices and Research Directions*, in Green Energy and Technology Series, 333 p. https://doi.org/10.1007/978-3-319-54199-0

Bao, H, Knights, P, Kizil, M and Nehring, M, 2023a. Electrification Alternatives for Open Pit Mine Haulage, *Mining*, 3(1). https://doi.org/10.3390/mining3010001

Bao, H, Knights, P, Kizil, M and Nehring, M, 2023b. Productivity estimation of battery trolley mining truck fleets, *Int J Min Reclam Environ*. https://doi.org/10.1080/17480930.2023.2278013

Bao, H, Knights, P, Kizil, M and Nehring, M, 2024. Energy Consumption and Battery Size of Battery Trolley Electric Trucks in Surface Mines, *Energies*, 17:1494. https://doi.org/10.3390/en17061494

Cunanan, C, Tran, M-K, Lee, Y, Kwok, S, Leung, V and Fowler, M, 2021. A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles and Hydrogen Fuel Cell Electric Vehicles, *Clean Technol,* 3(2):474–489. https://doi.org/10.3390/cleantechnol3020028

Ertugrul, N, Kani, A P, Davies, M, Sbarbaro, D and Morán, L, 2020. Status of Mine Electrification and Future Potentials, in *2020 International Conference on Smart Grids and Energy Systems (SGES)*, IEEE, pp 151–156. https://doi.org/10.1109/SGES51519.2020.00034

Feng, Y and Dong, Z, 2020. Optimal energy management with balanced fuel economy and battery life for large hybrid electric mining truck, *J Power Sources*, 454:227948. https://doi.org/10.1016/j.jpowsour.2020.227948

Global Mining Guidelines Group (GMG), 2022. Recommended Practices for Battery Electric Vehicles in Underground Mining, Version 3. Available from: <https://gmggroup.org/wp-content/uploads/2022/06/2022-06-23_ Recommended-Practices-for-Battery-Electric-Vehicles-in-Underground-Mining.pdf>

Halim, A, Lööw, J, Johansson, J, Gustafsson, J, Van Wageningen, A and Kocsis, K, 2022. Improvement of Working Conditions and Opinions of Mine Workers When Battery Electric Vehicles (BEVs) Are Used Instead of Diesel Machines—Results of Field Trial at the Kittilä Mine, Finland, *Mining Metallurgy and Exploration*, 39(2):203–219.

Kalantari, H, Sasmito, A P and Ghoreishi-Madiseh, S A, 2021. An overview of directions for decarbonization of energy systems in cold climate remote mines, *Renew Sustain Energy Rev,* 152:111711. https://doi.org/10.1016/j.rser.2021.111711

Knibbe, R, Harding, D, Cooper, E, Burton, J, Liu, S, Amirzadeh, Z, Buckley, R and Meehan, 2022. Application and limitations of batteries and hydrogen in heavy haul rail using Australian case studies, *J Energy Storage*, 56:105813. https://doi.org/10.1016/j.est.2022.105813

Leonida, C, 2020. Battery-electric Vehicles: Brightening the Mining Industry's Future, *Engineering and Mining Journal*, 221(1):32–37.

Li, J, Wu, X, Xu, M and Liu, Y, 2021. A real-time optimization energy management of range extended electric vehicles for battery lifetime and energy consumption, *J Power Sources*, 498:229939. https://doi.org/10.1016/j.jpowsour.2021.229939

Mazumdar, J, 2011. Performance improvement of mining haul trucks operating on trolley systems, in *2011 IEEE Industry Applications Society Annual Meeting,* IEEE, pp 1–6.

Moore, P, 2022. Surface Mining Trucks, *International Mining*, 17:50–67.

Plazas-Niño, F A, Ortiz-Pimiento, N R and Montes-Páez, E G, 2022. National energy system optimization modelling for decarbonisation pathways analysis: A systematic literature review, *Renewable and Sustainable Energy Reviews*, 162:112406.

Power Sonic, 2024. What is a battery C rating, *Power Sonic*. Available from: <https://www.power-sonic.com/blog/what-is-a-battery-c-rating/> [Accessed: 1 October 2023].

Ritter, A, Elbert, P and Onder, C, 2016. Energy Saving Potential of a Battery-Assisted Fleet of Trolley Buses, *IFAC-Pap,* 49(11):377–384. https://doi.org/10.1016/j.ifacol.2016.08.056

RPMGlobal, 2024. HAULSIM, RPMGlobal. Available from: <https://rpmglobal.com/product/haulsim/> [Accessed: 1 April 2024].

Shaobo, X, Qiankun, Z, Xiaosong, H, Yonggang, L and Xianke, L, 2021. Battery sizing for plug-in hybrid electric buses considering variable route lengths, *Energy*, 226:120368. https://doi.org/10.1016/j.energy.2021.120368

Terblanche, P J, Kearney, M P and Knights, P F, 2018. Potential of on-board energy recovery systems to reduce the costs of diesel-electric mine truck haulage, *Mining Technology.* https://doi.org/10.1080/25726668.2018.1451611

Valenzuela Cruzat, J and Valenzuela, M A, 2018. Modeling and Evaluation of Benefits of Trolley Assist System for Mining Trucks, *IEEE Trans Ind Appl,* 54(4):3971–3981. https://doi.org/10.1109/TIA.2018.2823261

Zuliani, J E, Guilbaud, J and Carreau, M, 2021. Decarbonisation of remote mine electricity supply and vehicle fleets, *CIM Journal*, 12(4):135–148.

Deriving maximum value from mineral waste streams

D Osborne[1]

1. Industry Advisor, Somerset International, Brisbane Qld 4000.
   Email: dosborne@somersetpty.com

INTRODUCTION

Current mineral extraction and valorisation activities still have a strong focus on the 'delivered product(s)' which might be a bulk commodity such as metallurgical coal, hematite, bauxite, etc., and mineral concentrates such as metal sulphides, oxides, and carbonates; precious metals, such as gold, silver and PGMs, REEs or battery metals; halogen salt forming elements; or industrial minerals, which are non-metals including crushed rock, sand, and gravel etc. With the current focus on tailings disposal the pushback has been to seek alternatives to the currently 'conventional' disposal method via increasingly higher risk tailings settling facilities (TSFs) with a changing focus towards 'dry disposal'. Whichever option is selected, the alarming trend is the increasing cost and ESG impacts. An emerging approach is to pose a focusing question 'Is there anything else passing into the tailings stream and/or disposable waste streams which could be recovered and pass into the product revenue stream? All of the above 'primary' process streams offer opportunities for increasing recovery and offsetting some of the disposal costs. Some secondary opportunities are already being pursued, such as REEs and battery metals from base metals deposits, but other opportunities are still being overlooked, such as building materials and soil conditioning pellets. These potential 'new' product streams can also utilise other mining and domestic wastes such as smelting slags, glass waste, plastic waste etc. This paper will address these opportunities and provide examples including process approach, economics and some of the current barriers that exist, which are holding back progress on such initiatives.

SOMERSET INTERNATIONAL APPROACH

Over the past decade, Somerset International has developed several innovative process systems to augment the original, patented Sub325® system first introduced in 2009. The pivotal technology is a uniquely configured solid bowl centrifuge which, since it was first introduced, has been developed, designed, installed, and operated in systems that uniquely treat ultrafine particles, mostly smaller than 30 microns. These feedstocks are encountered in processing plant tailings streams, recovering value, and properly disposing of the barren waste, avoiding where possible discharge into tailings storage facilities or disposal ponds.

Such systems assist in addressing several mining industry challenges, including:

- Declining ore grades: Ore grades are declining globally, so miners must extract more material to produce the same amount of mineral. This can lead to lower productivity and higher costs.
- Mine tailings disposal constraints: Mine waste and its disposal is increasingly more difficult due to rising regulatory pressure following the tragic dam collapses in Brazil and other environmental awareness.
- Water scarcity: The industry is being pressured to increase recycling and reduce freshwater consumption in many arid mining regions.

These issues have the potential to become critical ones given the dramatic expansion of the mining industry over the past two decades, with global production of mineral fuels, metal ores, and industrial minerals amounting to 17.3 billion tons in 2020, an increase of 52 per cent from 11.3 billion tons in 2000.

Additionally, the growing demand for mined raw minerals essential for emerging low-carbon technologies serve to compound existing challenges.

The presentation includes descriptive material of the Somerset Sub325 system in various applications where ultrafine metallurgical coal is recovered in compliance with a product specification, whilst a barren tailing is dewatered and returns process water the plant as well as creating a handleable cake for co-disposal with the other plant waste stream. This offers an opportunity of a mine to move from tailings storage to 'dry' disposal by generation of a low moisture cake. Following on from over 30 successful fine coal recovery installations in the US, Australia and elsewhere, Somerset has moved towards replicating these successes in the treatment of minerals and investigating if other value can be derived from the feed stream. In these developments strong partnerships have been developed with equipment vendors supplying the centrifuge and the beneficiation equipment, specifically flotation and magnetic separation as well as with research providers.

Collaborative research with two Australian universities led to the development of beneficiation and pelletisation of the barren tailings material to create a variety of new products for use as road base for mine haul roads and soil additives for rehabilitation via a research project with the Australian Coal Industry Research Program (ACARP). A local NSW company that participated in this program had been producing building products such as bricks, blocks, pavers, retaining wall blocks etc which are being used in local building projects.

At the same time, Somerset had commenced work on projects with various mineral producers towards valourisation of the tailings streams to replicate the successful outcomes achieved with metallurgical coal. Iron ore operations in Brazil, phosphate in northern Africa, PGMs in South Africa and Nickel in the Philippines, have all been effectively tested and trialled at commercial scale. Going forward, the company will soon be operating Sub325® systems along with the incorporation of either flotation or magnetic separation, to enable delivery of ultrafine mineral concentrates at or better than grade.

There is little doubt that a bright future will emerge for companies that offer solutions to respond to growing environmental issues, diminishing returns in the minerals sector, rising investment and operating costs and localised constraints, ie:

- Reduction in water consumption.
- Compliance for mine water discharge.
- Compliance with the Global Industry Standard on Tailings Management.

In response to these issues, the key steps for a tailings management program are to:

- Reduce waste generation by maximising commodity recovery.
- Create immediate water recovery by efficient dewatering.
- Expand tailings dewatering capacity and/or eliminate tailings slurry settling facilities.
- Seek opportunities for recovering other valued commodities from the tailings stream.

Future skills and workforce evolution

Experiences from developing a road map to attractive, inclusive and safe mining workplaces

L Abrahamsson[1]

1. Professor, Luleå University of Technology, Luleå 97187, Sweden.
   Email: lena.abrahamsson@ltu.se

EXTENDED ABSTRACT

The aim with this paper is to discuss experiences from the ongoing research project '*Attract: A roadmap to attractive, inclusive, and safe mining workplaces'*. The project's aim is to analyse possibilities, effects, and consequences of the green and digital transformation in the Swedish mining industry from workplace, socio-technical and gender equality perspectives. The research project (2022–2025) at Human Work Science at Luleå University of Technology is financed by the strategic innovation program Swedish Mining Innovation (a joint venture by the national research funds Vinnova, Formas and the Swedish Energy Agency).

The project includes a multidisciplinary research group of five senior researchers and five PhD-students and a broad repertoire of methods, eg literature reviews, qualitative interviews with both managers and workers, workplace observations, workshops, surveys, and project seminars where the researchers and the company representatives together analyse the results. One important part of the project is the applied approach where the researchers work together with two mining companies and one subcontractor company. The project has two parallel main subprojects.

The first subproject, '*The digital and green miner'*, is exploring how the implementation of autonomous technology will change the work for the miners and also what the mining work of the future will mean for workplace learning, competence development, and the possibilities to build attractive workplaces? We study operators, maintenance personnel, production-related officials and contractors. Preliminary results indicate that the introduction of autonomous louders in an open pit mine fundamentally will change the work. Many people who work closest to autonomous technology have a background as manual louder drivers. For them, the difference is greatest since the work are becoming both more responsible and complicated. Another significant difference is the increased safety of both loading and transport. We also see an increased emphasis on skills such as creativity, flexibility, and collaboration skills, but also mining-specific knowledge. Learning needs to become a natural part of the work to handle the new green and digital technologies and the mining companies are now starting processes to create learning organisations for the existing staff.

The second subproject, '*GenSafe'*, is studying what prerequisites is needed in the workplace culture at multi-employer mine sites to develop a safe and inclusive mining culture. We are studying the relationship between gender equality and safety in workplace culture and how working methods and methods that stimulate a safe and inclusive mining culture throughout the supply chain can be developed. Our studies show that there are cultural communities at the workplace that exclude others. Inclusion in the community seems to require various forms of adaptations ('entrance exams'), being there for one's colleagues and 'tolerating jokes', in ways that sometimes risk counteracting both safety and inclusion. The ability to fit in is partly about gender, but also about interests and where you came from. In other words, the norms of the local workplace culture seem to be about being a man and a woman in the 'right way'. Our studies also show that the work with safety has been more clearly integrated into the operations in a far mor formal, concrete, and direct way than gender equality. This applies both to the work with the mining company's own staff and in the joint work together with the contractors. One way to promote a safer and inclusive mining culture therefore seems to be to strengthen the gender and gender equality perspective in the existing safety work. How this could be done, both in relation to the company's own staff and in the supply chain, will be an important question for the continued project to investigate.

The preliminary results show that new complex situations are emerging in the mining industry's work with electrification, circular material flows, digitalisation, and automation. Both the new technologies as well as the use of them affect and are affected by people and workplaces and the organisation of work, safety and learning. To support the functionality of the green and digital technology and at the

same time develop inclusive, attractive, and safe workplaces there is a need of research that places people (all types of women and men) in the centre of technological development. Our next step in the project will be to develop a roadmap for attractive, inclusive and safe mining together with the participating companies. How should technological development be combined with social and human perspectives to create an attractive, healthy, and safe work environment?

Perspectives and initiatives for the future of mining

A Binder[1], P Foster[2], S Hazuria Anderson[3], L Liu[4], N Mojtabai[5], S Nowosad[6], S Raval[7], O J Restrepo Baena[8] and R Webber-Youngman[9]

1. Clausthal University of Technology, Germany. Email: angela.binder@tu-clausthal.de
2. University of Exeter, England. Email: p.j.foster@exeter.ac.uk
3. Curtin University, Australia. Email: sakshi.anderson@curtin.edu.au
4. Chongqing University, China. Email: zhliuli@cqu.edu.cn
5. New Mexico Tech, USA. Email: navid.mojtabai@nmt.edu
6. Clausthal University of Technology, Germany. Email: sandra.nowosad@tu-clausthal.de
7. University of New South Wales, Australia. Email: simit@unsw.edu.au
8. School of Mines, Universidad Nacional de Colombia, Colombia. Email: ojrestre@unal.edu.co
9. University of Pretoria, South Africa. Email: ronny.webber@up.ac.za

INTRODUCTION

As the mining industry faces times of change, new challenges arise to ensure raw material supply for the younger and future generations. Different scenarios are currently shaping the way we mine and teach mining engineering. Led by an increasing demand for raw materials, net zero requirements for improving long-term operation performance, technological advancements such as automation and digitalisation, safety improvements, environmental considerations and a need for social acceptance, mining is pursuing to change and adapt to these requirements at a faster pace.

Such changing times raise new concerns, one of the most relevant is the lower number of students interested or enrolling in mining engineering and related fields leaving mining engineering as one of the less preferred career options between the younger generations. Nonetheless, it is essential to continue addressing and supplying the skill sets that is suited to contemporary and future of the mining industry. To this end, globally, academia is currently undergoing several initiatives such as curricula updates and adaptation, up skilling, improving teaching practices and techniques, including e-learning techniques, enhancing industry-academia and inter-university collaboration, and much more.

SOCIETY OF MINING PROFESSORS (SOMP)

The Society of Mining Professors, originally established as Societät der Bergbaukunde, is a vivacious Society representing the global academic community. SOMP represents the global mining scientific community as it gathers more than 300 members from all five continents, including 50 countries, and 123 universities. Furthermore, SOMP is committed to make a significant contribution to the future of the mineral's disciplines having as main goal to guarantee the scientific, technical, academic, and professional knowledge required to ensure a sustainable supply of minerals for mankind. To achieve this, SOMP facilitates information exchange, research and teaching partnerships and other collaborative activities among its members driven through seven working committees and six award committees. Once a year, SOMP members meet at an Annual General Meeting (AMG), to share and discuss about tendencies, teaching best practices, emerging topics in both research and education in mining engineering disciplines.

MINES OF THE FUTURE

Since the publication of the SOMP *Mines of the Future* report (Saydam *et al*, 2019), the world has seen a changing environment however the principles and the vision for future mines based on five main topics—operational efficiency, novel mining systems, sustainable mining practices, education, and research—instead of becoming obsolete are nowadays more valid and relevant than ever. Furthermore, the pandemic catalysed a significant push towards digitalisation across various sectors, including mining, propelling industries forward in adopting technological solutions. In response to disruptions caused by restrictions and safety measures, the mining sector embraced digital tools and automation to ensure operational continuity while safeguarding workers' health. Contemporary mining is defined by a rising demand for primary and secondary extraction of raw materials, specially enhanced by the need for critical raw materials to achieve a just right transition, enhanced by supportive regulatory frameworks and policies. At the same time, geological orebodies are increasing in complexity and depth. In an evaluation of more than 1000 mining projects around the globe, 150 mining projects represented mines that transition from surface to underground operations or are in the process of the transition (Nowosad and Langefeld, 2023). The mines of the future take along higher technical challenges in the fields of productivity, ventilation, seismicity, ground control, geomechanics, tailings management, extractive technology in processing, mine closure, implementation and deployment of technological changes related to automation, electrification and digitalisation, new business models, and moreover the need for a younger, agile, and capable workforce. Along this, academic institutions as in the case of the USA, face a shortage in the number of students interested on pursuing mining majors as well as with recruiting postgraduates and educators able to drive the newer generations towards a more complex but sustainable future.

SOMP STAKE FOR EDUCATION

Acknowledging the need to address these challenges and benefiting from the active participation of academia representatives attending the AGMs, SOMP develops different activities related to mining engineering education. This presentation highlights two of the recent workshops conducted by the Education Committee, to identify emerging topics in mining engineering education. In 2022, during the AGM in Namibia with a participation of around 80 members, emerging topics mining academia is currently not addressing properly were defined. The top five identified emerging topics in 2022 were automation, artificial intelligence, entrepreneurship, diversity, and digitalisation. Meanwhile, in 2023, the top five identified topics were sustainability, innovation, systems thinking, intergenerational equity and communication. Additionally, a third workshop was conducted in 2023 to define the technical and interpersonal skills necessary to drive change in the mining industry for the future mines. Hereby the top five technical skills were environmental acknowledgement, technical expertise in general, programming, project management, smart and big data management. Meanwhile the top five interpersonal competences identified were communication, leadership, social awareness, emotional intelligence, and community awareness. These findings helped to develop a joint definition of the mining engineer of the future as a driven individual and competent engineer with curiosity and creativity who applies general technical mining skills in a globalised world, who fully understands the mineral value chain and its relevance for modern life, who is able to work in a multidisciplinary team environment with the major goal of enhancing and driving the sustainable extraction of raw materials.

Therefore, this paper presents, a qualitative analysis and overview on the technical and interpersonal skills mining engineers will have to develop and will be necessary to succeed and lead in the mining industry, especially when enhancing all aspects of sustainability. It introduces and describes the perspectives from universities around the globe involving seven different countries in five continents America, Europe, Asia, Africa and Oceania and put them in a context with the working points of the Society of Mining Professors (SOMP) through its Education Committee. Finally, a selection of initiatives by the involved universities are showcased and country specific demands and challenging scenarios are described.

REFERENCES

Nowosad, S and Langefeld, O, 2023. Global Trends in Mining – Correlation between mining methods and technology development for future mines, in Second International Conference 'Resources and Technology' RESAT 2023 (German-Mongolian Institute for Resources and Technology: Mongolia).

Saydam, S, Hebblewhite, B, Karmis, M and Hitch, M, 2019. Mines of the Future, Society of Mining Professors / Societät der Bergbaukunde (SOMP).

Systems thinking and its need in the workforce of tomorrow

D Brown[1] *and K Markovic*[2]

1. Systems Engineer, Nova Systems, Fremantle WA 6160.
   Email: daniel.brown3@novasystems.com
2. Systems Engineer, Nova Systems, Fremantle WA 6160.
   Email: kristina.markovic@novasystems.com

ABSTRACT

The world is becoming an increasingly complex environment to operate within. Adoption and evolution of technology is occurring at a rapid pace and operating spaces are growing in interconnectedness and interdependency. In mining this is evidenced by the large-scale adoption of autonomous machinery, intelligent systems, Internet of Things (IoT) devices, and robotics to realise benefits in optimisation, productivity, and safety. To enable continual delivery and growth in operational performance, and to realise the aforementioned benefits, a new approach for managing mining and metals is required (Mining Review Africa, 2023). This means that an already talent constrained workforce must learn to manage the complexity inherent, evolving, and growing in the environment (Abenov *et al*, 2023). A key skill that needs to be further developed and deployed to combat these challenges and to enable robust problem solving is that of systems thinking, which is already practiced in pockets within the mining industry. Experience and learning can be leveraged from other industries and their application of systems thinking to ensure that focus is maintained on areas where the benefits from which will be optimised. With targeted application, a workforce capable of effective systems thinking can be the catalyst to optimisation across mining organisations.

INTRODUCTION

Systems thinking

Systems thinking focuses on systems in terms of complexity, interrelationships, context, emergence, and wholes from holistic viewpoints (Lamb and Rhodes, 2008). Systems thinking is a complementary mindset that places emphasis on the complete system, system-of-systems, or problem and its relationships with its environments, as opposed to traditional approaches to problem solving where problems and systems are broken down into manageable parts. Note that in this context, a system is an arrangement of elements (hardware, software, people, supply chains, processes, information etc) that when integrated exhibit behaviour or meaning beyond that of the constituent elements alone (INCOSE, 2023). Systems thinking does not remove the need for deep technical specialty, nor the need to logically decompose systems and problems, rather, systems thinking serves as a toolset that anyone within the workforce can use as a foundation to frame problems and enable educated decision-making. It is even suggested by Beasley and Ingram (2020) that when applied effectively, systems thinking can enable innovation.

Systems thinking in other industries

Other industries across the world train their workforces in systems thinking to aid in the mitigation of the risks associated with complexity, integration, and uncertainty. The defence, aerospace, and space domains are prime examples of this both locally and internationally. In these domains, systems thinking is used to mitigate risk, deliver solutions on time and on budget, and provide assurance that specifications are met (Greeff, 2012). Systems thinking is applied within multidisciplinary teams across the life cycle of a system to frame domain-specific efforts whilst ensuring system wide alignment. Through this application, systems are effectively managed such that they are proven to be fit for purpose in their intended environment across their life cycle, are adequately specified and considered in terms of interfaces and interconnections and are proven to exhibit desired emergent functionality. Critically, complexity and uncertainty are not removed through the application of systems thinking. Rather, applied systems thinking ensures that knowns and unknowns are identified, captured, defined, and planned for as much as possible. Through this, systems thinking limits unexpected outcomes, enables robust, dynamic forward planning, and promotes educated and informed decision-making.

Application in mining

As a problem-solving mindset, systems thinking is already applied by individuals and teams across the mining industry, however, this is only in patches, not expansively across organisations. As evidenced by other industries, greater benefit from the approach could be realised. To maximise the benefits offered by robust systems thinking, development of these skills within the following two areas of the mining workforce should be focused upon.

Projects and studies

Particularly in the early stages of the project/system life cycle, systems thinking offers significant potential to reduce risk. Applied systems thinking at this phase will:

- Enable a strong understanding of the project or system's environment and expectations, reducing risk during introduction to operations.
- Define interconnections and interdependencies, reducing risk and rework during build and integration.
- Enable identification and specification of enabling system elements and fundamental inputs to the system such as personnel, policies, and procedures, which will ensure that the right pieces are placed around the system to sustain it over its life during operations and maintenance.
- Align specialised engineering efforts and teams and frame them within the context of the system, increasing efficiency in development and scheduling.
- Provide a means to integrate and manage schedule, cost, and risk, which will support projects from total cost of management and ownership perspectives.

Applying systems thinking this early in the life cycle will provide greater confidence that the project or system being delivered is right for its environment and will meet expectations and specifications.

Asset and project management

In both areas, robust systems thinking supports and enables educated and informed decision-making. Systems thinking provides system-wide context to problems being addressed and provides insight beyond that which lies on the surface, largely when it comes to decision implications. This broader perspective enables focused and system-wide trade-off analysis to be conducted. This extends to maintenance optimisation through prioritisation of system level Key Performance Indicators (KPIs).

Specific to project management, systems thinking reduces the risk of a key problem, that being re-work (Mawby and Stupples, 2001). This is achieved through the identification, recognition, and management of uncertainty provided by systems thinking. This in turn, can support improvement in project outcomes on a large scale (Mawby and Stupples, 2001).

CONCLUSION

To combat the growing complexity in operations, the mining industry must invest in systems thinking to equip and strengthen the workforce. Through application of systems thinking based on learnings from other industries, the mining workforce of tomorrow will be capable of managing evolving risks rising from complexity, uncertainty, technological advancement, and interconnectivity of systems. Without this holistic approach, the mining industry may struggle to maintain its reputation for operational excellence and may need to search for other means of optimisation.

REFERENCES

Abenov, T, Franklin-Hensler, M, Grabbert, T and Larrat, T, 2023. Has mining lost its luster? Why talent is moving elsewhere and how to bring them back [online]. Available from: <https://www.mckinsey.com/industries/metals-and-mining/our-insights/has-mining-lost-its-luster-why-talent-is-moving-elsewhere-and-how-to-bring-them-back> [Accessed: 25 March 2024].

Beasley, R and Ingram, C, 2020. How Systems Engineering and Systems Thinking Enable Innovation, *INCOSE International Symposium*, 30(1):1032–1048. https://doi.org/10.1002/j.2334-5837.2020.00770.x [Accessed: 24 April 2024].

Greeff, A P, 2012. Systems thinking in the planning of military operations, *INCOSE International Symposium*, 22(1):2173–2187. https://doi.org/10.1002/j.2334-5837.2012.tb01465.x [Accessed: 24 April 2024].

International Council of Systems Engineers (INCOSE), 2023. *Systems Engineering Handbook* (eds: D Walden, T Shortell, G Roedler, B Delicado, O Mornas, Y Yew-Seng and D Endler), fifth edition, pp 2 (John Wiley and Sons).

Lamb, C T and Rhodes, D H, 2008. Collaborative Systems Thinking Research: Exploring Systems Thinking within Team, *INCOSE International Symposium*, 18(1):222–233. https://doi.org/10.1002/j.2334-5837.2008.tb00802.x [Accessed: 15 April 2024].

Mawby, D and Stupples, D, 2001. Systems Thinking for Managing Projects, *INCOSE International Symposium*, 11(1):126–132. https://doi.org10.1002/j.2334-5837.2001.tb02283.x [Accessed: 24 April 2024].

Mining Review Africa, 2023. Making change more holistic: Using systems thinking to drive next-level operational excellence [online]. Available from: <https://www.miningreview.com/tech-news/using-systems-thinking-to-drive-next-level-operational-excellence/> [Accessed: 24 April 2024].

The RockDataAcademy – a new open-access knowledge base covering the ins and outs of using sensors to scan ores

M Dalm[1]

1. Founder, RockDataWorks, Rijswijk, The Netherlands. Email: m.dalm@rockdataworks.com

INTRODUCTION

More and more mining companies are becoming aware of the potential benefits of sensor-based ore sorting and process optimisation. This is reflected by a growing number of analysers that are available for drill hole logging, conveyor belt scanning, ore sorting, slurry analysis, etc. These tools all rely on a specific sensor technology that can be used to detect a material property such as colour, density, mineralogy, or chemical elements. However, all sensors have restrictions on the minerals and/or elements that can be detected or inferred. This is caused by the physical mechanisms behind the technology and depends on mineral concentration and compositional heterogeneity of the ore. Since nearly every ore deposit is unique in composition and characterised by different geological features that drive heterogeneity, no one-size-fits-all sensor solution is available. This makes it difficult for mining professionals to find suitable sensing technologies that can help them solve problems and improve processes for their specific ore types.

CHALLENGES IN SENSOR SELECTION

A large variety of sensing techniques can be used to detect important ore properties. Building a scanner can be as simple as mounting a camera over a conveyor belt to detect differences in colour or texture of the ore that is being transported. This can already provide useful information when clear visible differences occur between the ore and waste rock for example. Commercially available sensor systems range from such ad hoc systems to million dollar scanners that use nuclear sources or lasers to interrogate the ore materials. However, high investments on scanning equipment can be difficult to justify, especially for small-scale operations. A higher price also does not necessarily provide a better solution. It depends on the type and quality of the information that the sensor provides and how it is used to add value to the mining process.

In order to compare different sensors and identify the best potential solutions for a specific mine site, information is required on the characteristics and restrictions of the different sensing technologies. Examples of characteristics that are generally important are contrast and detection limit. Contrast refers to how well a certain material property can be distinguished from other features that appear in the measured sensor signal. For a regular camera this means how well the colour of a certain material class can be distinguished from the colour of other classes (eg ore versus waste, high- versus low-grade, oxide versus sulfide etc). For sensors based on spectroscopy, contrast refers to how well the spectral signature of an element or mineral of interest can be distinguished from those of other elements. The spectral signatures of different elements sometimes overlap, which means that contrast can be affected by the presence of other components. Because of this, measurement of arsenic with an X-ray fluorescence (XRF) sensor for example can be problematic when the ore has relatively high lead contents (Deslattes *et al*, 2005). Another example is the laser-induced breakdown spectroscopy (LIBS) sensor for which high iron contents can obscure the signatures of many other elements (Kramida *et al*, 2023).

The detection limit refers to the lowest concentration of a mineral or element that can be measured with a sensor. Detection limits depend on the sensing technique as well as the hardware configuration that is used to perform the measurements. Detection limits can therefore differ between sensor systems that are based on the same working principles. Additionally, the detection limit is usually not the same for all elements or minerals and can sometimes also be affected by other material properties. In near-infrared (NIR) reflectance spectroscopy for example, the detection limit often depends on the overall reflectivity of a rock. On very dark rocks, detection limits are usually higher because less light is reflected and the features that are related to mineral occurrence are less pronounced. This shows that detection limit and contrast are also related to each other.

Publicly available information on the possibilities and limitations of different sensing technologies for measuring ores and rocks is largely restricted to academic papers. These are all scattered throughout a variety of journals, conference proceedings, and websites. There is no easy way to search all the different sources and find information on sensor applicability for specific ore types and commodity elements. Mining companies therefore often need to rely on technology providers to correctly inform them on the potential feasibility of sensor systems. However, technology providers could be biased in their evaluations and may be unaware of alternative sensing techniques or sensor combinations that can provide a better solution.

ROCK DATA ACADEMY

The RockDataAcademy is a new open-access knowledge base on all the ins and outs of using sensors to scan ores in mining. It consists of a series of articles on topics such as the opportunities and benefits of using sensors in mining, the possibilities and limitations of the different sensing technologies, and important aspects in sensor application development. It also provides guides and tables to assist in selecting suitable sensing technologies for specific ore types and evaluating analyser and sorter feasibility. The aim is to help mining companies with finding the best sensor solutions for their operations and support the development and integration of ore sensing applications.

All articles and other information are published on the platform under a creative commons licence (CC BY-NC) and are freely accessible to anyone. Quality of the published information is secured through the support of universities and sensor technology providers.

The RockDataAcademy is continuously expanded with new articles and other features. Planned future additions include video presentations, a discussion forum, and a search database to find other relevant literature by sensor, deposit, or commodity type. Additionally, online workshops will be offered for more in-depth learning on how sensor-based ore analysis and sorting can be used to improve mining processes.

Development of the RockDataAcademy is motivated by the vision that the introduction of sensors into mining processes promotes a more responsible utilisation of the Earth's mineral resources. How that works is described throughout the articles on the platform. Please visit www.rockdataworks.com/rockdataacademy to learn more.

REFERENCES

Deslattes, R D, Kessler, E G, Indelicato, P, de Billy, L, Lindroth, E, Anton, J, Coursey, J S, Schwab, D J, Chang, C, Sukumar, R, Olsen, K and Dragoset, R A, 2005. X-ray transition energies database (version 1.2), [online]. Available from: <http://physics.nist.gov/XrayTrans> [Accessed: April 2024].

Kramida, A, Ralchenko, Y, Reader, J and NIST ASD Team, 2023. NIST Atomic Spectra Database (version 5.11), [online]. Available from: <https://physics.nist.gov/asd> [Accessed: April 2024].

Beyond the manufacturing mindset – adapting workforce skills for the tech driven mining industry

Y Lanwin[1]

1. Founder and CEO, Sans Prejudice Solutions, Perth WA 6008.
   Email: yhana@sansprejudicesolutions.au

ABSTRACT

The Australian mining sector is undergoing a significant transformation with the adoption of advanced technology to the operational landscape. This has highlighted a critical disconnect between our traditional educational systems and the skill requirements of working with these advanced technologies. This paper aims to provide a behavioural science analysis of how the traditional manufacturing mindset, deeply rooted in our educational frameworks from primary to tertiary education, registered training organisations (RTOs), and in-house learning and development, is misaligned with the needs of today's technologically advanced mining operations.

Originating in the industrial revolution, the manufacturing mindset prioritised efficiency, mass production, and the division of labour. In educational institutions, this translated into an emphasis on rote learning, linear examinations, and a rigid adherence to processes and procedures. Such a system, while effective in producing a workforce suited for repetitive and predictable tasks, falls short in fostering skills like problem-solving, adaptability, flexibility, and coping with change – skills that are increasingly vital in a mining sector dominated by automation, robotics, and AI.

The paper discusses how the focus on disciplined adherence to standard work procedures and processes in educational and training programs has inadvertently stifled creativity and autonomy in learners. This issue is compounded in the workplace, where employees, having been conditioned to operate within strict guidelines, now face the challenge of adapting to environments where autonomous decision-making and creative problem solving are crucial.

In essence, the traditional approach to education and training has prepared individuals for a world of work that no longer exists. This paper advocates for a whole of pipeline approach, grounded in behavioural science, to revamp mining education and training. It highlights the importance of understanding and influencing the behavioural aspects of learning and recommends for an approach that promotes diversity, critical thinking, and adaptability, preparing the workforce to excel in the rapidly changing landscape of the Australian mining sector.

INTRODUCTION

The Australian mining industry is at the cusp of a significant transformation, driven by the rapid adoption of advanced technologies such as automation, robotics, and artificial intelligence (AI). This technological evolution has brought to light a critical disconnect between traditional educational systems and the contemporary skill requirements necessary for thriving in a tech-driven mining landscape. Historically rooted in the industrial revolution, the manufacturing mindset has influenced educational frameworks from primary to tertiary levels, including registered training organisations (RTOs) and in-house learning and development programs. This mindset, which prioritises efficiency, mass production, and the division of labour, has shaped an education system focused on rote learning, standardised assessments, and rigid procedural adherence. While effective in preparing a workforce for repetitive and predictable tasks, this approach falls short in cultivating essential skills such as problem-solving, adaptability, and creative thinking—capabilities that are increasingly vital in the modern mining sector. The manufacturing mindset itself has evolved, with mining companies now chasing productivity and value realisation through a combined lens of process optimisation and a culture of improvement. This paper explores the misalignment between traditional educational paradigms and the needs of today's technologically advanced mining operations, advocating for a comprehensive, behaviourally informed overhaul of mining education and training to better equip the workforce for future challenges.

THE EVOLUTION OF THE MANUFACTURING MINDSET

The manufacturing mindset, originating in the late 18th century during the Industrial Revolution, revolutionised production methods and organisational structures. Major milestones include the emergence of mechanised production processes, such as the invention of the spinning jenny (1764) and the water frame (1769) by James Hargreaves and Richard Arkwright, respectively, marking the beginning of mass production. In the early 20th century, Henry Ford's implementation of the assembly line in automobile manufacturing at the Ford Motor Company's Highland Park Plant (1913) epitomised the manufacturing mindset's focus on efficiency and standardisation. This approach proliferated further with the post-World War II era, witnessing the widespread adoption of Taylorism, or scientific management principles developed by Frederick Winslow Taylor, emphasising systematic approaches to optimise efficiency and productivity in manufacturing processes. The late 20th century saw the rise of Lean Manufacturing methodologies, which further emphasised eliminating waste and maximising value-added activities in production processes. These principles found application not only in traditional manufacturing but also permeated industries like mining, where safety, efficiency and productivity were paramount. The evolution of the manufacturing mindset from the late 20th century onwards has culminated in what is now known as Industry 4.0. This latest evolution of industry is characterised by the integration of digital technologies such as automation, robotics, and artificial intelligence as the mindset shifts towards interconnected, smart production systems.

The manufacturing mindset has profoundly influenced not just production methods but also organisational cultures and operational strategies in the mining industry, however the disconnect between processing efficiency, systems and workforce skills is growing. The latest evolution of the manufacturing mindset is an informal methodology aimed at improving operational efficiency and reducing defects or errors by combining principles from Lean Manufacturing, Six Sigma (Wheat, Mills and Carnell, 2001) and 'The Toyota Way' (Liker and Meier, 2006). The following key principles apply.

Eliminate waste

This principle focuses on eliminating waste and maximising value-added activities. In mining, this translates to streamlining workflows, reducing downtime, and optimising resource utilisation. For example, Lean techniques such as value stream mapping can help identify and eliminate non-value-added activities in mining processes, improving overall efficiency.

Minimise errors and defects

This principle on the other hand, emphasises data-driven decision-making and reducing variation to achieve consistent and predictable outcomes. In mining operations, Six Sigma methodologies can be applied to enhance product quality, minimise variability in production processes, and reduce the likelihood of errors or defects.

Long-term philosophy and challenge

Prioritising sustainable practices over short-term gains to ensure environmental and economic viability in the future. In mining this could involve investing in environmentally responsible extraction methods that minimise ecological impact, ethical mine development or prioritising long-term sustainable outcomes over individual short-term incentives.

Right process will produce right results

Optimising processes to achieve high-quality outcomes while minimising waste. For example, a mining operation may implement lean practices to reduce overproduction of some material types, streamline transportation processes, and eliminate variability in the final product, improving overall efficiency and profitability.

Recognition of the value of employees

Valuing employees involves empowering them to contribute to continuous improvement and fostering a culture of collaboration and innovation. For instance, mining companies may implement initiatives such as leadership development programs targeted at those who live the company's values and involving their extended network of suppliers and strategic partners in improvement initiatives, leading to improved safety, productivity, and job satisfaction.

Solving root problems drives organisational learning

Embracing an inclusive problem-solving philosophy that requires contribution from managers and teams to promote organisational learning and adaptation. For example, mining companies may encourage managers to personally assess operational challenges (genchigenbutsu) and facilitate consensus-based decision-making processes (nemawashi) to swiftly address root issues and drive continual improvement. Additionally, fostering a culture of reflection (hansei) and innovation (kaizen) enables mining companies to evolve and remain competitive in a dynamic industry landscape.

The Toyota Way is often proposed to be split into a People Pillar covering respect and teamwork and a Continuous Improvement Pillar covering challenge, kaizen and genchigenbutsu. Multiple studies however have shown that in implementing the Toyota production system, along with other earlier iterations of the manufacturing mindset, that the People Pillar elements are often deprioritised, misunderstood or not supported by the same education and training rigour as the 'harder' elements of the system to the detriment of its overall efficacy (Vanichchinchai, 2023).

EVOLUTION OF MINING WORKFORCE SKILLS

Mapping the mining workforce demographics and skills over the decades can provide some insights into both the successes and failures of the manufacturing mindset.

1980–2000

The Australian mining industry diversifies with world-class deposits including zinc, copper, gold, nickel and magnesite added to the existing portfolio of iron ore, nickel and coal. FIFO labour model established, shifting infrastructure investment away from regional towns (Australian Bureau of Statistics, 2000) and attracting an almost entirely white male workforce due to the challenging rosters and intense physical labour. Alcohol use was high, with safety standards and regulation only just beginning to penetrate the industry following previous decades of high fatality and injury rates. Normalised behaviours in line with many other male-centric industries included hazing of new joiners and exclusion and harassment of minority groups. The mostly low-skilled workforce begins to be supported by standardised work practices, task segregation and on-the-job training facilitated by internal company experts.

2000–2020

Boom and bust cycle leads to the rise of the contract labour market which resulted in an influx of overseas works. These workers are either employed on the controversial 457 temporary work visa filling unskilled positions or through permanent work sponsored placements in roles outlined on the critical skills shortage list. Work health and safety legislative changes and technology advances in the last 5–10 years has led to a more accessible workplace environment coupled with sustained high wages has resulted in increased in workforce diversity (Foo and Salim, 2022). With mining scale and complexity expanding as well as compliance and regulatory oversight, registered training organisations (RTOs) emerge in an attempt to battle the skills shortage and de-risk organisations from having permanent internal training departments (https://www.voced.edu.au/vet-knowledge-bank-history-vet-milestones). Trade qualifications become an established part of the skills pipeline into mining with apprentices and skilled tradespeople from a variety of industries attracted to the industry by the high wages, and businesses adopt continuous improvement methodologies from the manufacturing mindset. This, coupled with the economic cycle variability leads to an environment of contestant change.

2020–2040

In Australia, the mining skills shortage is now seen as structural rather than cyclical, with high wages and industry workforce stability offset by often low retention levels at an individual company level, partially attributed to psychologically (MARS Program, 2023) and physically unsafe (Community

Development and Justice Standing Committee, 2022) work environments, particularly for women and other minority groups. Automation and digital transformation are now synonymous with the industry and process optimisation through technology is rapidly shifting organisational systems, processes and structures. Gen Z, the first ‘digital natives’ have entered the workforce while legacy equipment and infrastructure from the 1980s is still in operation.

THE MANUFACTURING MINDSET IN EDUCATION AND TRAINING

The infusion of the manufacturing mindset into education and training by necessity in the post WWII era has had long lasting impacts on all levels of education spanning primary, secondary and tertiary institutions, including Higher Education and vocational education and training (VET) equally in Australia. This mindset, originating from the industrial revolution, emphasises discipline, standardisation, individual success or failure and adherence to rigid processes. However, over the last two decades, significant shifts have occurred, not only in the manufacturing sector but also in education theory. Concepts such as personalised learning, self-directed experiential learning, and the recognition of diverse learning styles have gained prominence, reflecting a departure from traditional, rigid educational practices.

Despite the rapid evolution of educational theory, the widespread adoption of these progressive concepts has been sluggish within Australian education institutions. Particularly in the tertiary VET sector, there remains a prevalent one-size-fits-all approach to education, which is failing to meet the dynamic needs of industries such as mining. This failure stems from a disconnect between educational practices and the rapidly changing demands of the workforce, particularly in mining where advanced technologies and automation are now a given. As a result, the mining industry continues to face challenges in finding adequately skilled workers who can navigate the complexities of modern mining operations. Addressing this gap requires a paradigm shift in tertiary education towards more flexible, adaptive, and industry-aligned curriculum designs that embrace the inclusive and equitable design principle and the modern manufacturing principles of innovation and continuous improvement.

Primary and secondary education

Over the past four decades, primary and secondary education in Australia has undergone notable transformations in both pedagogy (child and adolescent learning theory) and educational philosophies. Traditional rote learning methods, prevalent in the 1980s and 1990s, have gradually yielded to more student-centred approaches, emphasising critical thinking, creativity, and problem-solving skills. The late 20th century saw the integration of technology into classrooms, with interactive digital tools and online resources becoming indispensable educational aids. Simultaneously, there emerged a heightened awareness of the importance of inclusive education, accommodating diverse learning needs and abilities, particularly in the 2000s. There has been a growing emphasis on holistic development, with increased attention to social-emotional learning and values-based education alongside academic achievement, a trend that has gained momentum in the 2010s. This evolution reflects a broader shift towards personalised, inquiry-based learning experiences aimed at equipping students with the skills necessary to navigate the complexities of the 21st century.

That being said, primary and secondary education is still largely measured both in terms of success and funding, by national standardised testing such as NAPLAN and ATAR, which by its nature excludes some learners and de-values the experience of others. Research on standardised testing as a route to improve overall education performance has been disproved over multiple studies (Tienken and Mullen, 2015) and change, while slow, has at least started. The 2023 Australian Senate inquiry (The Senate, 2023) into school refusal showed an alarming trend in secondary school attendance with the proportion of full-time students in compulsory schooling years (1–10), who attend >90 per cent of possible schools days declining from longer term averages of around 77 per cent to less than 50 per cent in 2022. Recommendations from the report include increased flexibility in education delivery, better identification and support for neurodivergent young people and young people with mental health challenges and a more balanced focus between student well-being and academic achievement.

Tertiary education

Tertiary education, encompassing post-secondary institutions offering programs beyond the secondary level, includes universities, vocational education training institutes such as and registered training organisations (RTOs) and technical and further education (TAFE). Tertiary education plays a crucial role in preparing individuals for advanced careers and fostering intellectual and personal development.

Andragogy, a term coined by educator Malcolm Knowles in the 1970s, refers to the theory and practice of adult learning. It emphasises self-directed learning, active participation, and the incorporation of learners' life experiences into the educational process.

Heutagogy, a concept introduced by Stewart Hase and Chris Kenyon in the early 2000s, builds upon andragogy by focusing on self-determined learning. Heutagogical approaches encourage learners to take ownership of their learning journey, set their own goals, and actively seek out resources and experiences to achieve them. This learner-centred approach prioritises autonomy, critical thinking, and lifelong learning skills essential for navigating the complexities of the modern world.

Universities

Over the past four decades, university education has experienced significant transformations influenced by evolving pedagogical approaches and external factors such as technological advancements and global events. The emergence of andragogy, or adult learning theory, has prompted a shift from traditional lecture-based teaching towards more interactive and learner-centred methods, tailored to the diverse needs and experiences of adult learners. The integration of technology into higher education has transformed teaching and learning, with online platforms, digital resources, and multimedia tools becoming integral to modern academic settings. However, the COVID-19 pandemic, which disrupted the world in 2020, hastened the adoption of remote learning and compelled universities to swiftly adapt to virtual teaching modalities. This shift has cemented the inclusion of multi-modal learning approaches into curriculums, reflective of societal demands for flexible and accessible education.

Additionally, universities have increasingly prioritised curriculum design as a means to engage and retain students over multiple years. This entails a focus on creating dynamic and engaging learning experiences that build over time to cater to diverse student needs and interests while aligning with industry demands. Universities are also now allocating significant resources towards enhancing student support services, industry collaboration and placements to facilitate long-term student success and progression.

The emergence of the micro-credential ecosystem, while unregulated, represents a step towards a heutagogy based learning model whereby education is focused, financially and practically accessible and learner-led. While high profile international universities including Harvard, Oxford and NUS have led the commercialisation of these courses, Australian Universities, not-for-profits and companies are rapidly adopting the model with great success.

Vocational education and training (VET)

The vocational education and training (VET) sector in Australia comprises of public TAFE institutes and independent Registered Training Organisations (RTOs). Courses offered include formal trade qualifications like Certificate III in Mechanical Fitting, Electrotechnology Electrical and Technical Engineering and statutory governed courses including Certificate IV in Work Health and Safety, Working at Heights and Forklift Training.

Unlike primary education, and to a lesser extent universities, the VET sector has faced challenges in keeping pace with the rapidly evolving demands of the workforce, particularly in industries like mining undergoing automation and technological advancements. While sectors like construction and manufacturing traditionally formed the backbone of VET programs, the emergence of automation, artificial intelligence, and digitalisation has reshaped the skill landscape. However, VET has been slower to adapt, struggling to incorporate not only shifts in adult learning theory, but also in the provision of training for emerging occupations and digital skills. This lag in course development and delivery has arguably contributed to the structural labour shortage, with industries experiencing difficulty in finding adequately skilled workers to meet their evolving needs.

The findings of the recent Parliamentary Inquiry: Shared vision, equal pathways: Inquiry into the perceptions and status of vocational education and training. Parliament of Australia (2024) clearly highlighted that the traditional building blocks of VET based on the historic manufacturing mindset including training packages and units of competency were failing to keep pace. Workforce homogeneity and standardisation of skillsets, while relevant for the labour intensive production processes of the past, falls short in the modern, let alone the future, production processes required in mining and other production based industries. Furthermore, the inquiry found a significant cultural issues within the VET sector where gendered violence and discrimination and harmful stereotypes about women's aspirations and capabilities were causing poor participation of women and further exacerbating the skills shortages.

Registered Training Organisations (RTOs) have also drawn scrutiny regarding their educational quality outcomes, as assessed by contemporary adult learning theories and the evolving needs of workplaces. Often characterised by standardised delivery methods, including full-day, classroom-based, rote-learning, theory-intensive sessions with a heavy reliance on multiple-choice assessments dating to the 1980s the primary function of many RTOs appears to centre around regulatory compliance rather than holistic educational outcomes. Despite the prevalence of RTOs as primary VET providers, evidenced by approximately 90 per cent of VET students nationally opting for RTOs over TAFE colleges, and a substantial portion of the mining workforce entering the industry through VET pathways, concerns regarding the adequacy of program design and delivery in this sector persist.

Education sector collaboration

It is essential to acknowledge the historical and hierarchical disconnect within the education system as a whole. Universities, TAFEs, and RTOs have often struggled to collaborate effectively, resulting in cultural and behavioural challenges within the mining industry, notably an 'us versus them' mentality between engineers with university degrees and those with technical engineering qualifications through VET. The lack of mutual respect between these organisations has hindered solution development. For instance, individuals with a University Postgraduate Certification or Masters in Education are required to complete a Certificate IV in Training and Assessment to teach in industry. Conversely, those with a Certificate IV in Training and Assessment may not receive recognition of prior learning if they want to become a teacher or lecturer. Such examples underscore the need for improved collaboration and mutual recognition within the education sector.

TOP THREE SKILLS DEVELOPMENT CHALLENGES FOR THE MINING INDUSTRY

The Australian mining industry stands at a pivotal juncture, grappling with a host of challenges in skills development as it navigates the complexities of the modern workforce landscape. This is increasingly evident as failures of the manufacturing mindset can arguably be attributed more to the lack of workforce skill development prior to entering the workforce and capability development once in industry than to the processing methodologies themselves (Gaiardelli, Resta and Dotti, 2019). Key among these challenges are:

The workforce of the future has been let down by an education system of the past

- *Generation Z Dynamics:* Gen Z, born between 1995 and 2009, has undergone education in an era marked by standardised, rote learning approaches. However, workplaces now demand critical thinking, problem-solving, and collaboration skills. This misalignment between education and workplace requirements has led to issues like career churn, mental health concerns, and engagement issues, making this cohort particularly high-risk.
- *Generation Alpha Expectations:* The subsequent generation, Gen Alpha (born between 2010 and 2024), is beginning to benefit from changes in primary education towards student-centred

approaches. However, a rapid shift in tertiary education is imperative to bridge the gap between educational practices and the evolving needs of the workforce.

The traditional mining workforce pool alone does not have the capacity to succeed in the future of work

- *Obsolete Workforce Dynamics:* The traditional mining workforce, characterised by a male-centric demographic, focused on physical strength, low-skilled roles, and a preference for command-and-control leadership styles. However, these attributes are no longer conducive to the future of mining, which demands diversity of thought, experience, capability, and growth potential.
- *Mandate for diversity:* There is a growing mandate for diversity within the mining industry, strongly aligned with the collaborative principles of the Toyota Way. Cultural shifts are imperative to overcome biases, structural barriers, and systemic challenges, fostering an environment where a diverse workforce can thrive and lead the industry into the future.

Learning theory aligned with the modern manufacturing mindset exists, however whole of education system shifts are required to implement

- *Andragogy and respect:* Concepts like Andragogy, emphasise self-directed learning, active participation, and the incorporation of learners' life experiences into the educational process. Similarly, as identified in the Toyota Way (Vanichchinchai, 2023) respect for diversity of thoughts, beliefs, and experiences is crucial for fostering an inclusive learning environment.
- *Heutagogy and teamwork:* The Toyota Way principles of continuous learning and improvement at a company level, coupled with skills development and training for all staff, align with the heutagogical approach where employees define their learning journey and actively seek out resources to achieve their goals. This alignment presents a robust foundation for to solving root problems and driving continual organisational learning.

The convergence of these challenges underscores the critical need for the mining industry to adapt its skills development strategies to meet the demands of the future. With approximately 77 per cent of occupations in the sector considered enhanced or redesigned (EY, 2019), the industry's ability to plan learning campaigns to keep pace with data and digital skills required tomorrow becomes paramount. Embracing the manufacturing mindset, particularly the educational and training elements of the Toyota Way, is instrumental in addressing the existing skills gaps and preparing the industry for the challenges ahead.

A BEHAVIOURAL SCIENCE APPROACH TO CHANGE

Understanding the historical context of the manufacturing mindset and its implications for the education and training sector is crucial for mining companies aiming to address skills intervention challenges. While various public policy interventions are in progress in the primary and secondary sectors, others in the tertiary space are being reviewed, such as enhanced oversight and quality governance of Registered Training Organisations (RTOs) and the potential separation of the Vocational Education and Training (VET) sector into distinct categories of 'education' and 'training', with the former focusing on holistic student development and the latter targeting industry-specific competencies (Parliament of Australia, 2024). For mining companies, relying solely on policy changes is deemed too slow to bridge the skills gap. Instead, immediate action is necessary. Although some companies have established internal RTO capabilities and large learning and development organisations, they often fall victim to *status quo* bias, mirroring outdated leadership experiences and expectations. Additionally, learning and development teams composed solely of VET experts may perpetuate flaws from the education system, such as siloed thinking and standardised learning methods, which are misaligned with both workforce needs and the modern manufacturing mindset.

Opportunities for Mining Companies:

- *Tailored training programs:* Develop training programs catering to different learning preferences, recognising that diverse learning journeys can achieve the same learning outcomes. This might involve giving individuals the choice between practical competency assessments, self-paced digital learning modules, or peer-to-peer training (Gaiardelli, Resta and Dotti*,* 2019).
- *Advocate for a collaborative education system:* Advocate via peak bodies and directly with governments for an education system approach that fosters collaboration between secondary and tertiary institutions and industry stakeholders, valuing the unique contributions of each.
- *Diversify internal learning and development teams:* Diversify internal learning and development teams by including experts from secondary education, university education, and VET sectors, alongside technology and operations experts representing multiple generations.
- *Incorporate options for globally leading micro-credentials* – rather than invest significant resources in developing and maintaining behavioural based learning, seek out and incorporate options for individuals to participate in non-industry specific leadership, communications and cultural change programs through existing globally leading providers. These top University led courses are at the forefront of learning theory, and are digitally enabled making the price point significantly more accessible than in previous decades.
- *Technology-specific learning campaigns:* Keep pace with rapid changes through technology-focused learning campaigns (EY, 2019) that are multimodal, learner-centred, inclusive, and equitably designed.
- *Heutagogy-based educational approaches:* Develop educational learning journeys grounded in heutagogy, targeting the skill development gap between primary and tertiary education sectors and the modern manufacturing mindset. This includes fostering skills such as respect, teamwork, self-reflection, problem-solving, decision-making, valuing diversity, and continuous improvement.
- *Hiring practices based on manufacturing mindset skills:* Promote the hiring of diverse candidates by aligning screening and competency frameworks with the skills required by the modern manufacturing mindset.

To succeed, these opportunities demand significant investment and a departure from the *status quo*. Given that operational performance is influenced by employee behaviour, individual characteristics, and workplace design (Gaiardelli, Resta and Dotti*,* 2019), a behavioural science-based approach is recommended.

Behavioural science methodology

Behavioural science, drawing from psychology, economics, sociology, marketing, and neuroscience, offers a systematic method for studying human behaviour. The framework for applying behavioural science involves identifying specific challenges, formulating hypotheses, designing interventions, collecting data, and analysing results to refine strategies and achieve desired outcomes. This structured approach provides analytical rigour, waste elimination, and cost minimisation, ultimately facilitating successful skill development initiatives in the mining sector.

The framework for applying behavioural science to mining skills gap starts with identifying a specific challenge within the organisation, followed by formulating hypotheses about the underlying behavioural factors contributing to the problem. Next, an experiment or intervention is designed to target these factors, with clear data measurement criteria established. Data is collected and analysed to evaluate the effectiveness of the intervention, comparing against historical benchmarks or control groups. Conclusions are drawn based on the analysis, adjusting the experiment or refining the hypothesis as necessary. This structured approach leverages behavioural science to assess the impact of skills development initiatives within organisations, offering benefits such as analytical rigour, waste elimination and cost minimisation (which are often missing in the learning and development field), and ultimately quantifying and achieving desired results in skill development initiatives.

In addition to a scientific methodology, behavioural science also assists organisations with understanding the quality of their decisions based on empirical studies into human behaviour in decision-making scenarios. Heuristics are mental shortcuts that people make to cope with the enormous volume of decisions that need to be made every day. While useful in some scenarios, in the context of major organisational decisions these shortcuts can lead to errors in judgement and poor outcomes. Similarly biases, which are based on the cumulative impact of an individual's experience, narrow thinking and can lead to certain information being irrationally under- or overvalued. In the context of leading change for the future of work in the mining industry through education, the following are some examples that should be considered.

Groupthink

Groupthink exists where a desire for harmony or conformity results in irrational decision-making. This likely played a role in the failure of Toyota's production system during its major product recalls in the late 2000s, where insular culture and collective pressure to maintain the company's reputation led to safety concerns being quashed, ultimately compromising product quality and reputation. Similarly, in the mining education sector, groupthink has likely manifested where training programs are developed without critical external input, leading to outdated and ineffective curricula that have failed to address the evolving needs of the industry.

Availability heuristic

The availability heuristic causes individuals to overestimate the importance of information that is most readily available. This can lead to the prioritisation of recent trends over broader longitudinal data and also explains the drop in knowledge and skill seen between point-in-time training programs and follow up assessments months or years later. In the learning design space, this bias can result in training programs focusing solely on the latest technology without considering foundational skills necessary for long-term adaptability. Curricular developers may also overestimate the effectiveness of learning based on short-term data available including assessment results and in-classroom engagement. This data may have no correlation with longer term retained knowledge or the impact of learning on broader organisational outcomes.

Confirmation bias

Confirmation bias, or the tendency to search for, interpret, and recall information that confirms pre-existing beliefs, is another significant error trap. In the manufacturing mindset, this bias can hinder innovation, as organisations may only pursue process improvements that align with established practices, ignoring potentially transformative ideas. Within mining education, confirmation bias can lead to a persistence in traditional training methods, such as rote learning and standardised testing, despite evidence of the efficacy of more experiential and self-directed learning approaches. This resistance to change perpetuates a misalignment between educational outcomes and industry requirements.

By recognising and addressing these heuristics and error traps, mining companies and educational institutions can create more dynamic and effective training programs. Applying a behavioural science methodology, will further enable organisation to critically reflect and understand the efficacy of new approaches to ensure continued alignment to the vision of a workforce that is prepared and able to meet the demands of future mining operations.

CONCLUSIONS

The evolution of the Australian mining sector, propelled by advanced technologies like automation, robotics, and artificial intelligence, necessitates a corresponding transformation in education and training paradigms. The traditional manufacturing mindset, deeply ingrained in educational frameworks from primary through tertiary levels, has proven inadequate in fostering the critical skills required for modern mining operations. Heuristics and error traps such as groupthink, availability heuristic, confirmation bias, and *status quo* bias have perpetuated outdated training methodologies, stifling creativity, problem-solving, and adaptability among the workforce, and furthering the disconnect between those who have gone on a change journey within the industry, and the next generation of miners who have in many ways been failed by the education system.

To address these challenges, mining companies must embrace a behavioural science approach to education and training, promoting diverse perspectives, critical feedback, and continuous improvement, aligning learning theory with the latest interpretations of the manufacturing mindset. Individually tailored training programs, cross-collaboration between educational institutions and industry stakeholders, and the integration of modern learning theories such as andragogy and heutagogy are essential steps towards aligning workforce skills with the demands of a technologically advanced mining landscape.

By recognising and mitigating the impacts of cognitive biases and outdated educational practices, the mining industry can bridge the educational gap, and develop a diverse, dynamic and skilled workforce capable of navigating the complexities of future operations. This proactive approach will not only enhance operational efficiency and productivity but also foster a culture of innovation and resilience, cornerstones of the new manufacturing mindset, ensuring the sustained growth and competitiveness of the Australian mining sector in the global market.

REFERENCES

Australian Bureau of Statistics, 2000. Special Article - The Australian Mining Industry: From Settlement to 2000. Available from: <https://www.abs.gov.au/ausstats/abs@.nsf/94713ad445ff1425ca25682000192af2/93136e734ff62aa2ca2569de00271b10>

Community Development and Justice Standing Committee, 2022. 'Enough is enough' : Sexual harassment against women in the FIFO mining industry. Available from: <https://www.parliament.wa.gov.au/parliament/commit.nsf/(Report+Lookup+by+Com+ID)/EF1DF1A3F5DF74A848258869000E6B32/$file/20220621%20-Report%20No%202.pdf>

EY, 2019. The Future of Work: the Changing Skills Landscape for Miners, A report for the Minerals Council of Australia. Available from: <https://minerals.org.au/wp-content/uploads/2023/01/The-Future-of-Work-The-Changing-Skills-Landscape-for-Miners-February-2019.pdf>

Foo, N and Salim, R, 2022. The evolution of mining employment during the resource boom and bust cycle in Australia, *Mineral Economics*, 35(2):309–324. https://doi.org/10.1007/s13563-022-00320-8

Gaiardelli, P, Resta, B and Dotti, S, 2019. Exploring the role of human factors in lean management, *International Journal of Lean Six Sigma*, 10(1):339–366. https://doi.org/10.1108/IJLSS-08-2017-0094

Liker, J K and Meier, D, 2006. *Toyota Way Fieldbook*, 1st edition (McGraw-Hill Education). Available from: <https://www.accessengineeringlibrary.com/content/book/9780071448932>

MARS Program, 2023. The Mental Awareness, Respect and Safety (MARS) Program Landmark Study: Insights from the Worker Survey and Interviews. Available from: <https://www.curtin.edu.au/news/media-release/mining-worker-study-key-insights-into-the-state-of-wa-minings-mental-health/>

Parliament of Australia House of Representatives, 2024. Shared vision, equal pathways: Inquiry into the perceptions and status of vocational education and training, Canberra. Available from: <https://parlinfo.aph.gov.au/parlInfo/download/committees/reportrep/RB000170/toc_pdf/Sharedvision.equalpathways.pdf>

Senate, The, 2023. The national trend of school refusal and related matters, Education and Employment References Committee. Available from: <https://parlinfo.aph.gov.au/parlInfo/download/committees/reportsen/RB000090/toc_pdf/Thenationaltrendofschoolrefusalandrelatedmatters.pdf>

Tienken, C H and Mullen, C A, 2015. *Education Policy Perils*: *Tackling Tough Issues*, 1st edition (Routledge). Available https://doi.org/10.4324/9781315708713

Vanichchinchai, A, 2023. The relationships between soft and hard factors of the Toyota way: a socio-technical perspective, *Operations Management Research*, 16(2):768–779. https://doi.org/10.1007/s12063-022-00318-z

Wheat, B, Mills, C and Carnell, M, 2001. *Leaning into Six Sigma*: *The Path to Integration of Lean Enterprise and Six Sigma* (Pub Partners).

Ten conditions that will change the work of managers in Mining 4.0

J Lööw[1] *and J Johansson*[2]

1. Associate Senior Lecturer, Luleå University of Technology, SE-97187 Luleå, Sweden. Email: joel.loow@ltu.se
2. Professor, Luleå University of Technology, SE-97187 Luleå, Sweden. Email: jan.johansson@ltu.se

INTRODUCTION

There are many reports about how the new technology will affect our work, sometimes they are utopian but often dystopian. Most of the visions describe the industrial work, while the work of the managers does not seem to be affected. In this article, the authors will discuss how the new technology within the concept of Mining 4.0 changes the conditions for leadership and the work of managers in a modern mining industry.

METHODS

The empirical material comes from a study of organisational and social work environment in a big mining company in Sweden (Larsson *et al*, 2022) and three big European Union studies involving mining companies, technology developer and equipment providers; *Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future* (I^{2}mine), *Sustainable Intelligent Mining Systems (SIMS)* and *Next Generation Sustainable Intelligent Mining Systems (NEXGEN-SIMS).*

THE TECHNOLOGIES THAT ARE CHANGING MINING

Automation is intended to replace or minimise the human efforts in production, both the physical interventions and the cognitive ones. *Robots* and humans can be equipped with sensors of various kinds that make it possible to integrate it into an automated system. The automated system can then be integrated into larger systems through what is usually called the *Internet of Things*. Most of what happens in production, including the human interventions, is recorded and stored in databases, *Big data*, where you later can find patterns and structures in the data set, *Data mining*. With *VR and AR* technology, you can expand your senses and take in new types of information, you can simulate the course of events, you can look into the future before you need to act. With a production system that is fully represented in VR, you become less dependent on location. With *AI and machine learning*, control and decision-making are successively transferred to the machine, first as advice and then built into the systems. AI will almost always know better than yourself because it can base its decisions on a larger amount of data. The operators will increasingly be controlled by machine-generated algorithms, in its most extreme form it is described as algorithmic leadership.

BEING A MANAGER IN THE NEW DIGITISED CONTEXT

For managers of the future, the development means that she or he will work in a context that consists of fewer workers and more machines. Much of what used to be production control is now integrated into the autonomous systems and the personnel who remain in production will be well educated and make high demands on their work. In this context the managers will have access to sophisticated technology that gives both a good overview of the production and being able to get detailed information if needed. The overview is not limited to the present but applies both forward and backward in time. Forward in that different scenarios can be simulated and tested before decisions need to be made, backwards in that history can be reconstructed through all the information stored in big data. The future manager is also not dependent on location to the same extent as before. The mine follows wherever she or he goes, which can also mean never being able to leave the mine and must always be available, 24 hrs a day, seven days a week. Future managers can be in many places at the same time.

This new connected technology means that the world become bigger partly because she or he gains control over a larger part of the value chain and partly because the production system can be shaped independently of geographical distances. At the same time, you can experience the world getting smaller, so small that it can fit in a mobile phone. In parallel with geographical distances becoming less important, the linguistic barriers will also disappear where speech and texts can be easily switched between different languages.

The manager's decision domain will become more strategic when many of the operational decisions are integrated into the systems with the help of AI. A key issue then becomes when the strategic decisions become operational, and the manager is replaced by AI. It is a development that for sure will affect some lower managers, but the question is where the line is drawn. There is an obvious limit in that AI is based on a language-based model, which means that it cannot act on thoughts that have not yet been formulated and stored. Since AI will build on syntheses of what was previously formulated, the innovative companies that formulate new strategies could be a winner. Another decision domain that AI has difficulty handle is the ability to provide social support and exercise social control. As long as a mine is manned, an organisation for social support and social control is required. Here, an empathic ability is required, which has so far been reserved for humans.

CONCLUSIONS

In conclusion, the new technology will affect the managers' future work, but the development will not be as fast as for the miners. The authors cannot reliably describe what will happen, but they have summarised the technical discussion and formulated ten conditions that in one or another way will affect the managerial work of the future:

1. Routine work and dangerous work are automated and disappear.
2. The future work will mainly be to handle disturbances and train algorithms.
3. The managers become responsible for more capital that is distributed among fewer people.
4. With new technology, the world is growing at the same time as it is getting smaller, so small that it fits in a mobile phone. Having the mine in your pocket.
5. The work becomes independent of location. Future managers can be in many places at the same time.
6. The manager is expected to be available around the clock, every day of the year.
7. We are provided with expanded senses (memory, vision), one can see around corners.
8. You cannot escape from your history. Big brother sees and remembers everything.
9. Algorithmic leadership gets closer to the managers.
10. The manager's role is increasingly to function as social support and exercise social control.

It remains to formulate how the mining industry should meet these challenges; in the end it is not about technical determinism but human choices.

ACKNOWLEDGEMENTS

The study *Organisational and social work environment for managers* has been financed by the Swedish mining company LKAB and the three technical studies I²mine, *SIMS* and *NEXGEN-SIMS* are funded by the EU's research programs in collaboration with mining companies and machine suppliers.

REFERENCES

Larsson, J, Rapp, L, Roxenfalk-Jatko, K, Vinberg, S, Mattson Molnar, M, Johansson, J, Jakobsson, M and Lööw, J, 2022. Organisatorisk och social arbetsmiljö för chefer (Organisational and social work environment for managers), Luleå University of Technology.

Empowering mining communities – the importance of local business hubs for skills development

L Mackinlay[1]

1. CEO, Australian Business Volunteers, Sydney NSW 2000. Email: info@abv.org.au

ABSTRACT

The Apeketon Business Hub in Lihir, Papua New Guinea, emerged in 2019 through a partnership between Australian Business Volunteers (ABV) and Lihir Gold Limited (LGL), a subsidiary of Newmont Corporation. This development was driven by a shared vision for the Lihir gold mining operation to further enhance opportunities for the local community and strengthen the economy's resilience post-mine.

At its core, the business hub serves as the epicentre of ABV's operations in the region. It includes a drop-in resource centre which provides the community with mentoring and consulting services, and access to a range of impactful workshops facilitated by ABV's local staff and skilled volunteers. These workshops focus on local Lihirians but are open to the entire community, including Newmont employees. We design and continually refine Apeketon Business Hub support programs and offerings driven by community priorities, building trust through long-term relationships, and working side-by-side on real-time challenges.

We offer three core programs to different levels of the community, from individuals and families to start-ups, large corporations, and landowner groups. There is significant demand for the support services provided by ABV, with over 350 Lihirians participating in our workshops over the 2023 calendar year.

One of the hub's core offerings is the Family Money Management Program, which addresses crucial challenges faced by Lihir households, particularly in terms of financial resilience. The program takes a comprehensive approach, assisting families in long-term planning and developing skills to effectively manage the income they derive from their employment with LGL and other enterprises. Significantly, the program also addresses financial stress, a factor often associated with domestic violence (Fox *et al*, 2002). By empowering women and promoting joint financial decision-making, the Family Money Management Program fosters a culture of savings and improved financial management, ultimately enhancing economic resilience within the community.

INTRODUCTION

The Apeketon Business Hub (ABH) was established in 2019 by Australian Business Volunteers (ABV) in partnership with Lihir Gold Limited (LGL), a subsidiary of Newmont Corporation. ABH provides skills development programs that meet the social obligation requirements of LGL and benefits its employees and the local community where the mine operates (Chatterjee, 2023). The Apeketon Business Hub is community-led, which means that the program provides a comprehensive service driven by and for the Lihir community and is tailored to the unique local characteristics of the region. The Business Hub supports inclusive and sustainable economic development at all levels, from individual households to businesses and tenement landowner organisations.

This paper will examine the evolution of workforce skills in Lihir through the Apeketon Business Hub's support for nurturing talent in the local community.

THE 'S' IN ESG

The recent history of Environmental Social Governance (ESG) in the mining industry has seen the 'social' aspect become an increasingly important dimension to maintaining goodwill and trust with the community in which the company operates (Verrier *et al*, 2022). ABV recognises the need for a global shift in our approach to social impact, which can only be achieved through the development of sustainable and measurable social programs that are designed by and for the communities they serve.

LGL needed a robust plan as part of its ongoing commitment to develop local talent and skills, and ultimately fulfill its social obligations to the Lihir community in a sustainable and impactful way (Mancini and Sala, 2018). Newmont Corporation set the goal to prioritise employment of suitably qualified Lihirian staff at the mine. The ABH is designed to play an ongoing role in supporting and upskilling the community to fill roles with LGL. ABV and LGL formed a strong partnership, based on a mutual understanding of the significance of locally-led initiatives that promote innovation and constructive engagement with all key stakeholders, ranging from community leaders to government representatives.

The Apeketon Business Hub provides a dedicated space for ABV's Papua New Guinean staff to deliver impactful workshops in tandem with ABV skilled volunteers. It functions as an accessible drop-in advice centre, extending a helping hand to local businesses, community members and the Lihir workforce.

DELIVERING ESG OUTCOMES THROUGH COMMUNITY-LED PROGRAMS

The Apeketon Business Hub facilitates a range of signature training, coaching, and mentoring programs to deliver practical and impactful support over the short and long-term. ABH support programs are designed and continually refined, with offerings driven by community priorities. The focus is on building trust through long-term relationships and working side-by-side on real-life challenges. ABV's inclusivity and accessibility focus ensures ABH is available to community members across all clan groups, including remote villages see distribution (Figure 1).

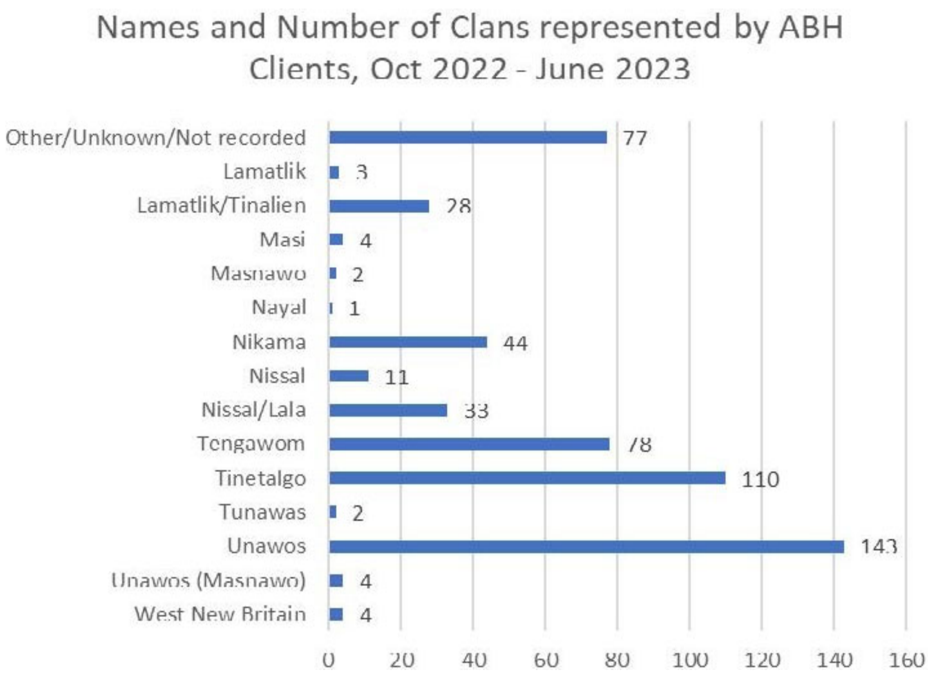


FIG 1 – Apeketon Business Hub outreach statistics 2022–2023.

There are three core programs offered year-round:

1. **Family Money Management Program (FMMP)** addresses crucial challenges faced by Lihir households, particularly financial resilience after mining activities. The program takes a comprehensive approach, assisting families in long-term planning and developing skills to effectively manage the income they derive from their employment with Newmont's Lihir operation and other enterprises.
2. **Your Enterprise Scheme (YES)** is utilising the industry experience of ABV's skilled business volunteers to assist start-ups through to established businesses. The program helps business owners tackle live challenges, leading to tangible business improvements and greater opportunities. After the initial training block for long-term support, participants can engage in ongoing mentoring and coaching from ABV's volunteers.

3. **Better Business Governance (BBG)** is targeted at company owners and directors and covers the principles of good governance, organisational structures, and the duties of Executives. ABH has worked closely with tenement landowner organisations to tailor our BBG Program to the specific needs of these landowners, addressing common challenges faced by their boards/executives and management teams.

Additionally, specialist skills workshops are held on an ad hoc basis, such as the Textile Workshop held in December 2023. A textile expert and ABV volunteer held a workshop on how to source, create and sell products from easily accessible materials. Over 60 people attended the free, half-day event.

OUTCOMES – SUSTAINABLE COMMUNITY-WIDE IMPACT

Apeketon Business Hub's services are in demand with 41 training courses held over the 2023 calendar year, attended by over 350 Lihirians. Feedback shows 83 per cent of businesses reported improvement in understanding their business operations (Australian Business Volunteers, 2023). However, the impact extends far beyond the individuals who attend the courses.

Our Family Money Management program addresses financial stress, a factor often associated with domestic violence. This program has majority female participation (see Figure 2). By empowering women and promoting joint financial decision-making, FMMP fosters a culture of savings and improved financial management, ultimately enhancing economic resilience within the community.

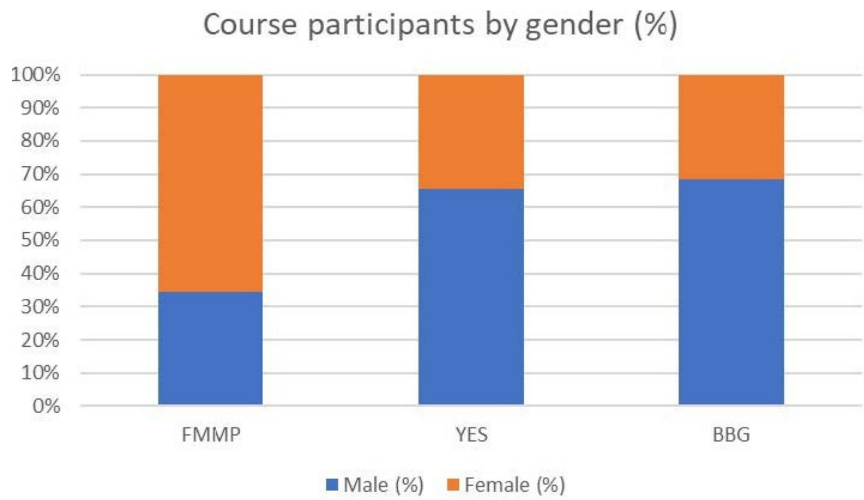


FIG 2 – Apeketon Business Hub gender participation rate across core programs, 2022–2023.

The wider community impact of the Apeketon Business Hub can be seen in the success stories of those involved in the programs such as Loise Kondiak and Rita Tzikmandion.

Loise first engaged with YES in 2019, and ABV's mentorship propelled Loise's business idea forward, allowing her to expand operations significantly. Alongside her family responsibilities, Loise operates a bus service for the local school and supports the mining operation during planned shutdown (maintenance work). Recently, Loise was able to purchase another bus for additional community transportation.

Rita Tzikmandion completed a FMMP training in 2023.

> *'I'm so grateful to have attended the FMMP training. I can now budget and save for the goals I set for myself. A lot of changes in terms of family co-operation has taken place. My husband and I have also opened a bank account to save our profits from the trade store for our future financial goal of expanding to a Supermarket. I was motivated to open the account after attending the FMMP training.'*

CONCLUSION

The Apeketon Business Hub is an example of successful community-driven development, demonstrating the transformative potential of local business hubs in promoting skills, resilience, and empowerment and collaboration with partners like Newmont to achieve this. Through expertly designed programs, ABV, in collaboration with LGL, supports sustainable growth for individuals, businesses, and the broader community of Lihir. With a focus on inclusivity, innovation, and long-term impact, this initiative highlights the importance of collaborative partnerships in driving significant change and building economic resilience.

ACKNOWLEDGEMENT

We acknowledge the strong partnership we have with Newmont through Lihir Gold Limited. Newmont is the world's leading gold company and a producer of copper, silver, zinc and lead. It is widely recognised for its principled environmental, social and governance practices across assets, prospects and talent anchored in favourable mining jurisdictions in Africa, Australia, Latin America and Caribbean, North America, and Papua New Guinea. We are proud of our ongoing collaboration with Newmont and look forward to continuing our journey together, guided by its values and clear purpose to create value and improve lives through sustainable and responsible mining.

REFERENCES

Australian Business Volunteers, 2023. Program Summary 2023. Unpublished internal company document.

Chatterjee, S, 2023. The Social Dimension of Sustainable Development: Human Capital Formation, Employment, and Education, T20 Policy Brief, Task Force 6: Accelerating SDGs: Exploring New Pathways to the 2030 Agenda, 20 p. Available from: <https://cuts-international.org/PDF/t20-policy-brief-orf-july-2023.pdf>

Fox, G L, Benson, M L, DeMaris, A A and Van Wyk, J, 2002. Economic distress and intimate violence: Testing family stress and resources theories, *Journal of Marriage and Family*, 64(3):793–807.

Mancini, L and Sala, S, 2018. Social impact assessment in the mining sector: Review and comparison of indicators frameworks. *Resources Policy*, 57:98–111. https://doi.org/10.1016/j.resourpol.2018.02.002

Verrier, B, Smith, C, Yahyaei, M, Ziemski, M, Forbes, G, Witt, K and Azadi, M, 2022. Beyond the social license to operate: Whole system approaches for a socially responsible mining industry, *Energy Research and Social Science*, 83:102343. https://doi.org/10.1016/j.erss.2021.102343

Are we there yet? Where the minerals industry is at, and where we are going with gender diversity, equity and inclusion

L H G McClean[1]

1. Managing Director, Forelight Advisory, Sydney NSW 2000.
   Email: lucy.mcclean@forelight.com.au

ABSTRACT

Diversity, equity and inclusion are often cited as 'important priorities' by mining companies and industry organisations in their public presentations and reports, but is the minerals industry really making strides forward?

The mining industry is the least gender diverse industry in Australia (WEGA, 2023). Women make up just 22 per cent of the mining workforce and mining has a gender pay gap of 15.1 per cent (WEGA, 2024a). Only 8 per cent of the CEO roles are female and 20 per cent of boards have no female members (WEGA, 2023, 2024a).

Gender diversity, equity and inclusion is a highly topical issue with the recent release of the Respect@Work report, Western Australia Parliamentary Inquiry as well as the publication of company specific workplace culture reports and the national legislative changes to implement a positive duty for organisations to prevent sexual harassment in the workplace. This comes at a time of a skills and labour shortage in the minerals industry as well as declining geoscience study and participation. This is a perfect storm for our future workforce.

Governments, industry associations, networks and companies are developing and supporting initiatives to make strides towards equity and inclusion, with some shining examples on both an industry and company level, but the dial is only moving slowly and, in some ways, going backwards.

Every company is unique, but every company can review and support gender diversity, equity and inclusion. Actions to progress gender parity could include establishing a clear company position; ensuring that this position is cascaded throughout the company with appropriate training; reporting and reviewing gender participation as well as supporting positive workforce initiatives and a positive culture with a people-centric issues reporting process.

At the industry level, there are clear gaps in the support for gender diversity and inclusion including a national voice and 'one-stop-shop' to support women in the industry and provide resources. Recommendations include improved co-ordination and collaboration of support for women as well as improved promotion of the suitability (and safety) of the industry for women. The new independent organisation, Women in Mining and Resources Australia (WIMARA) has the objective to address the challenges of gender diversity and inclusion as well as foster co-ordination, co-operation and collaboration between the different stakeholders and state or territory groups and amplify reach.

To deliver the future workforce that the minerals industry needs, the time is now for the industry to make some giant leaps for womankind.

INTRODUCTION

> *'It is good that you are doing this job as you are easier on the eye than the usual bloke'.*

This was a comment to a new (and first ever industry) female Chair of a well-known monthly mining industry event that featured leaders in industry presenting on their projects to an audience of over 150 attendees in a major capital city in Australia. The comment was made during question time at the event, so, in front of the entire audience. This did not happen in 1970 or 1980, but just recently, in early 2024.

Diversity, equity and inclusion are often cited as 'important priorities' by mining companies and industry organisations in their public presentations and reports, but is the minerals industry really making strides forward?

The industry has come a long way in some parameters, but has far to go to deliver gender diversity, inclusion and equity to support the workforce needed for the future of mining.

Note that in this paper, 'woman' or 'female' is taken to generally mean anyone who identifies as female.

WHERE ARE WE NOW?

Women are vastly underrepresented in the minerals industry.

The mining industry is the least gender diverse industry in Australia (WEGA, 2023). Women make up just 22 per cent of the mining workforce and mining has a gender pay gap of 15.1 per cent (WEGA, 2024a). Only 8 per cent of the CEO roles are female and 20 per cent of boards have no female members (WEGA, 2023, 2024a). The recent WEGA release of 115 Employers of Choice for Gender Equality citations (WEGA, 2024b) included five construction companies but not a single mining company, a damming fact for one of the largest industries in Australia.

Over the past 20 years, the number of women employed full-time in mining nationally rose from just 8700 in August 2002 to 45 000 in August 2022 (ABC, 2024). This is a significant increase, although there is also evidence that growth is now slowing. In NSW, mining is the most male dominated industry (11.7 per cent female) and in the past year, the gap has widened with male representation increasing 7.7 per cent (NSW Government, 2024a).

Internationally, the data on female representation is difficult to determine, especially as there are many unregister workers in artisanal and small-scale mining. According to International Labor Organization (ILO, 2021), some 21.4 million workers were employed in mining and quarrying in 2019, of which it is estimated that 18.3 million were men and 3.1 million (or 14 per cent) were women. The number of women has remained both low and relatively stable over the period 2000 to 2019, as shown in Figure 1.

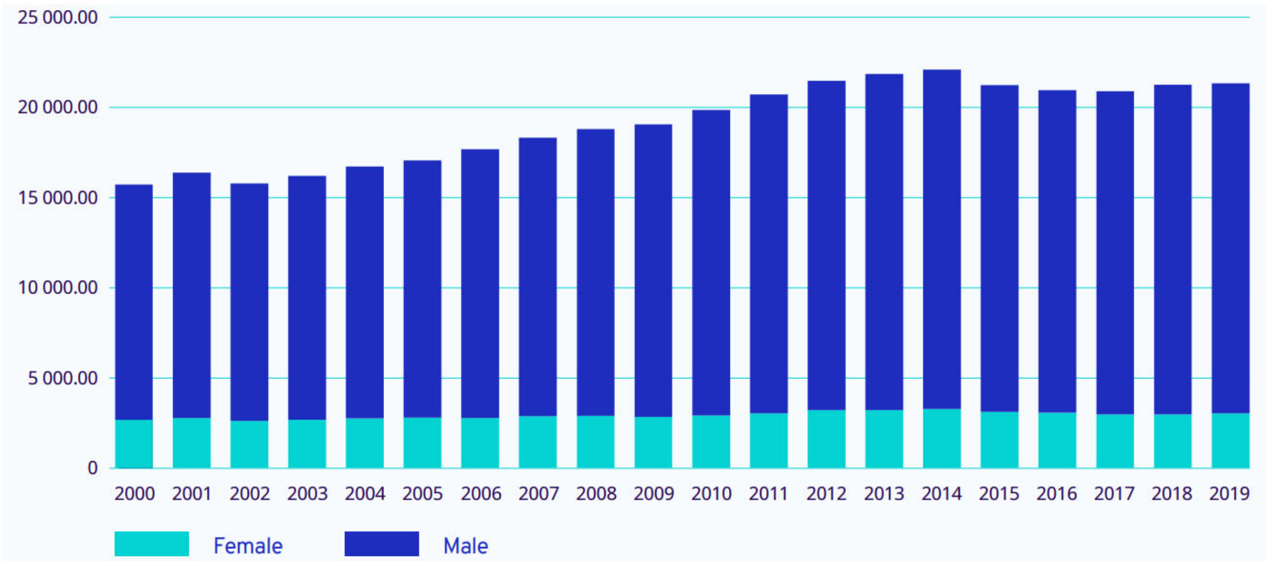


FIG 1 – Mining employment, by gender (2000 to 2019) in thousands (ILO, 2021).

From a study of 12 key mining jurisdictions (Intergovernmental Forum, 2023), Australia is noted as a leading jurisdiction for gender diversity with 15 per cent women, although well behind Sweden with 25 per cent women and Canada with 19 per cent women (Figure 2).

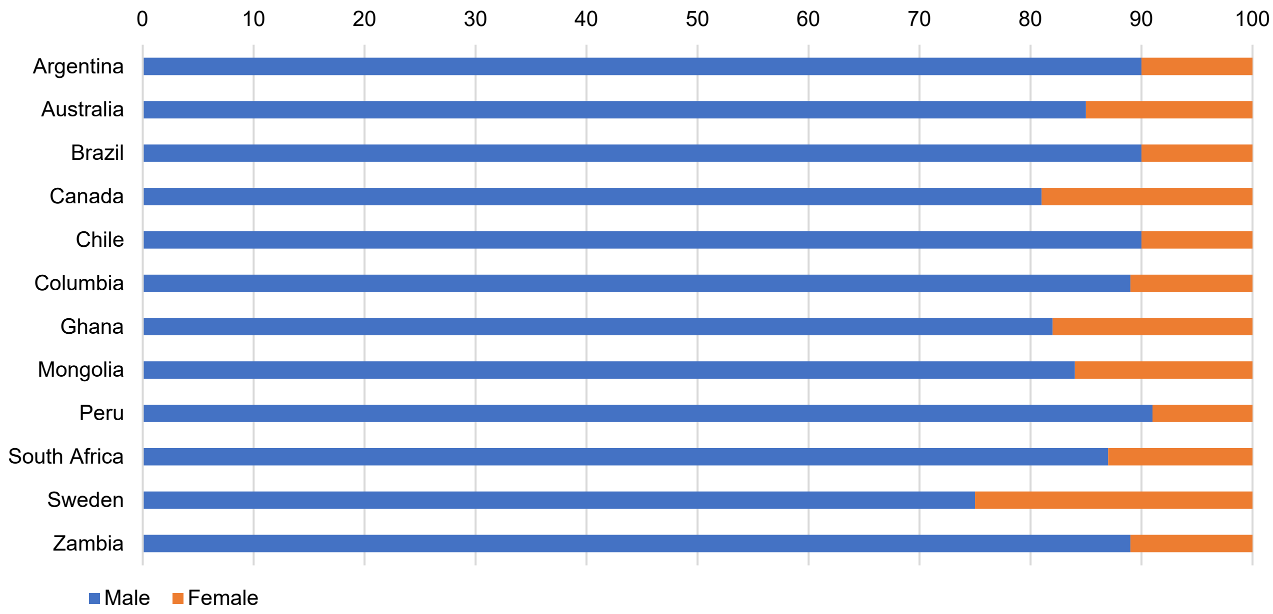


FIG 2 – Gender distribution by percentage in large-scale mining (adapted from Intergovernmental Forum, 2023).

HOW FAR HAVE WE COME?

It is important to remember that it is only in living memory when women were legally allowed underground in Australia and internationally.

Until 1986, Western Australia mine owners could be fined $500 if women worked underground, while NSW and Queensland only changed their laws in 1989 (Taylor, 2016; ABC, 2018). In other countries such as Papua New Guinea, it was only legal for women to work underground from the mid-1990s.

Even after the laws changed, it was still considered unlucky for women to be in an underground mine or taboo, with many reports of refusal of entry for women or women disguising themselves as men on field trips both in Australia and internationally.

It is also important to consider the wider participation of women in the workforce. It was only really due to the loss of working men to the World War in the 1940s when the women entered the workforce in wider industries beyond the traditional roles of teaching, nursing, domestic and administrative support. Women's participation in the workforce increased by 31 per cent between 1939 and 1943 (ABS, 2021). The bar for married women to work in the Australian Commonwealth Public Service was lifted in 1966, although it was many more years until it was not expected for pregnant women to leave their jobs.

Equal pay for men and women (ie equal pay for equal work) was granted in Australia in 1969 following the United Nations Universal Declaration of Human Rights principle of equal pay (Australian Government, 1998). The gender pay gap (ie the difference between average earnings of men and women, expressed as a percentage of men's pay) in Australia is currently 21.7 per cent (WEGA, 2024a) across all industries, 55 years after equal pay was legislated and at a time when over 60 per cent of women are employed and 64 per cent of women have attained a non-school qualification (ABS, 2024).

IS GENDER DIVERSITY REALLY IMPORTANT?

Today, it may be considered fair and just for women to be provided with equal work opportunities as men, but the business case is also important to understand.

Australian Institute of Management notes that prioritising gender diversity benefits include widening the talent pool and range of perspectives. Increasing the range of perspectives with gender diversity is positively correlated with innovation and that companies with a diverse workforce, especially in leadership roles, tend to be more innovative. Similarly, work groups with more women are better at knowledge sharing and collaboration (AIM, 2024). Companies that rank in the top 25 per cent of gender diversity are 21 per cent more likely to report above average profitability (Hunt *et al*, 2018). Improved talent attraction and retention is also important with 85 per cent of young women actively looking for employers with a strong policy on gender diversity and 61 per cent of women specifically review gender diversity in the leadership team when choosing a workplace (PWC, 2024).

Women are also important investors, with about 33 per cent of global wealth controlled by women (Bank of America, 2024) and the number of female investors on ASX rising – in 2023, 42 per cent of all investors and half of all intending investors are women (ASX, 2024). Positive workforce gender diversity has also been shown to trigger positive stock reactions both in data from Google and eBay and in randomised experiments (Daniels *et al*, 2024).

Bias due to gender remains a key consideration and has been noted as 'pervasive in work and in organisations, creating inequality at every stage of the employment cycle… decades of research has made one thing clear: gender biases are nearly always present in employment decisions' (WEGA, 2019). Recent public examples include the narrative around Katherine Bennell-Pegg, the first Australian astronaut (who is also female), and the USA Democrat nominee for President, Kamala Harris.

INCLUSION DRIVES DIVERSITY

Inclusion is an important part of improving gender diversity to support retention of women in the workplace.

There is a 'leaky pipeline' of women leaving STEM careers with many women leaving the back door of companies just as others are heralded arriving in the front door (Handley *et al*, 2020; EY, 2024). This loss is particularly significant from the minerals industry in childbearing years and beyond, leading to fewer women in leadership roles. The gender divide in industry numbers from students through to industry veterans is shown in the Australian Institute of Geoscientists (AIG) membership profile – student members are 34 per cent female, in comparison to 29 per cent of graduate members and 12 per cent member/fellow grade (Handley *et al*, 2020).

The World Economic Forum notes that there is a persistent gender inclusion gap that impacts women's opportunity for promotion or advancement and development of new skills (WEF, 2024). In the AusIMM Diversity and Inclusion 2024 Survey (AusIMM, 2024) of almost 700 people, inclusion in the resources sector rating as 'good or very good' reduced from 42 per cent in 2023 to 36 per cent in 2024, with 25 per cent of respondents (and 36 per cent of female respondents) rating inclusion in the resources industry as 'poor or very poor' in the latest report.

WHAT ARE THE CHALLENGES, WHAT ARE THE ISSUES?

In mining and the wider minerals industry, the traditional issues of the nature of the industry have been considered challenging for female participation. The work has been traditionally viewed as heavy and dirty, located in remote areas, generally with shiftwork and often fly-in, fly-out (FIFO) requirements that may not be viewed as 'female friendly' nor compatible with caring responsibilities. This is still an important consideration when the ABS reports that women have over a third more time in parental participation in childcare activities than men (ABS, 2024).

Workplace cultural issues are also an important factor in gender parity. Many companies may have shiny gender diversity policies and public statements that are not reflected in what happens on-site and away from 'Head Office'.

> *'He took me by myself into a room deep underground and told me that is not how things are done around here. I was terrified.'* – report from 18-year-old woman who had reported sexual harassment (pers comm).

Bullying and sexual harassment are topical issues in Australia following the publication of the Respect@Work report (Australian Government, 2022), rise of the #MeToo movement as well as the publication of workplace culture reports by two major mining companies and the WA Parliamentary Inquiry into sexual harassment of FIFO workers.

In the 2022 report into workplace culture at Rio Tinto (Elizabeth Broderick and Co, 2022) the survey of over 10 000 employees revealed that there was a 48.4 per cent rate of bullying experienced globally or 52 per cent for Australian employees where there was also a correspondingly higher rate of sexual harassment of 12.9 per cent. Gold Fields published a similar report into workplace culture in 2023 (Elizabeth Broderick and Co, 2023) from a survey of over 4000 employees where over half of the participants had experienced bullying, sexual harassment or racism in the past five years. The company notes that 'such practices, apart from the terrible human toll extracted, are also not good for the company's bottom line' (Gold Fields, 2023).

Few would believe that these issues are limited to these companies. Together with the data on gender inequality and government information, this points to a systemic industry culture.

This is supported by the recent AusIMM Survey (AusIMM, 2024) that reports that 24 per cent of women did not feel that they belonged or were connected with the resources sector. Half of women surveyed had witnessed gender inequality and bullying in the last two years and 16 per cent had experienced sexual harassment in the last two years – that is almost one in five women (Figure 3).

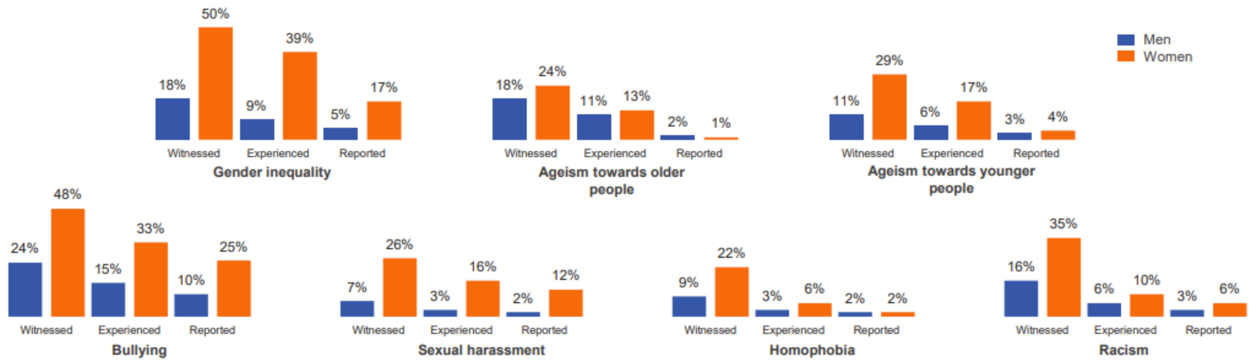


FIG 3 – Issues of the workplace and resources sector by gender (AusIMM, 2024).

This needs to change. Recent Australian legislative changes significantly expand the previous protections regarding sexual harassment. The changes that came into effect in March 2023 apply to workers, contractors, volunteers, work experience students, future workers and people conducting a business or undertaking. The changes prohibit sexual harassment associated with work and create a positive duty for employers to prevent sexual harassment, meaning that a person or company must prove that they took all reasonable steps to prevent sexual harassment (Australian Government, 2023).

FUTURE FITTING THE MINING INDUSTRY

This focus on gender inequality and harassment has come at a time of a significant labour and skills shortage for the industry (KPMG, 2020). At the same time, there has been a significant decline in students choosing geoscience, and tertiary institutions offering geoscience (Cohen, 2022), indicating a perfect storm for the pipeline for the future workforce.

To deliver the workforce of the future for the mining industry, KPMG (2020) notes that three key elements should be considered:

- embrace and accelerate technology
- enable remote working
- accelerating diversity.

To meet the objective of global decarbonisation, a significant uplift will be needed in mineral exploration and mining. By 2030, electricity storage alone will require 50 new lithium mines, 60 new nickel mines and 17 new cobalt mines, with an increased investment of US$100 billion annually (Minerals Council of Australia, 2024a).

Attracting talent for the minerals industry will be critical to success. Improving gender diversity, equity and inclusion will be an important component of the future workforce and investment in the future pipeline is needed to take the sector forward.

WHAT IS BEING DONE

'Enough is Enough' is the title of the recent report (Government of Western Australia, 2022) that clearly captures the sentiment on the appalling data on sexual harassment in the Western Australia FIFO mining industry, but also more broadly on gender issues and inequity.

The numbers do not lie, and there is a general consensus that more needs to be done to support gender inclusion, equity and diversity in the minerals industry.

Many companies, industry associations, governments and other stakeholders are actively leaning into the issue. Support to increase gender diversity, equity and inclusion in the minerals industry includes:

- **Toolkits, fact sheets and other resources** – Governments and other stakeholders including the Minerals Council of Australia have released resources to support gender diversity and industry specific information on sexual harassment including the Respect@Work toolkit (Minerals Council of Australia, 2024b), Western Australia Government's Mental Awareness, Respect and Safety (MARS) Program (Government of Western Australia, 2024), NSW Government's mandatory reporting for bullying and sexual harassment to the NSW Resources Regulator (NSW Government, 2024b).
- **Networking opportunities, professional development and mentoring** – Networking or professional development activities are offered by state or territory 'women in mining' group or groups including the Women in Mining Networks (WIMnets). Female specific mentoring is offered by women in mining groups in most states, with opportunities varying between different jurisdictions and region.
- **Focus on International Women's Day** – Many companies and industry organisations facilitate celebrations for International Women's Day on 8 March including the AusIMM lunch series in most capital cities and other celebrations by women in mining state or territory groups, as well as the recently nominated International Women in Mining Day on 15 June to provide focal points for activities.
- **National and state/territory awards** – State and National annual awards highlight leaders and programs that support gender diversity, noting that some awards have eligibility exclusions (for example membership of the organising association or specific industry sector).
- **National survey** – AusIMM publishes a national Diversity and Inclusion Survey, now in its sixth year in 2024.
- **Training on diversity and inclusion** – AusIMM has two online courses on diversity and inclusion developed for the minerals industry, with many companies also providing internal training.
- **Company internal initiatives** – Many companies have implemented programs and opportunities to support their female workforce including leadership programs, female student programs, mentoring, flexible working arrangements and generous paid parental leave opportunities. Examples include the BHP Bamboo Program that offers reduce working hours and company housing that '*ultimately… means that women can be the primary carer while maintain their careers*' (BHP, 2024); the Rio Tinto Aluminium Women in Leadership Program (Rio Tinto, 2023) that demonstrated increasing women in frontline leadership positions over 15 per cent in six months and the recent industry leading changes by Whitehaven to provide 26 paid weeks of parental leave including superannuation contributions for the primary care giver as well as ten days paid leave for domestic and family violence (Whitehaven, 2022).
- **Gender targets or quotas** – Some companies have published goals on gender diversity targets, subscribing to '*what gets measured, gets done'*. BHP set the '*aspirational goal*' in 2016 to achieve gender balance by 2025, at a time when the number of women in the company was

17.6 per cent (BHP, 2020). Another major company (who shall remain nameless) currently has a target of 20 per cent female employment and 20 per cent in leadership roles by 2026.

- **Company reports** – Companies including Rio Tinto and Gold Fields have boldly published detailed reports on issues with gender diversity, sexual harassment and bullying. Others have undertaken studies but not made the findings publicly available. A growing number of minerals industry companies are producing annual Sustainability or ESG (environmental, social and community) reports, some of which include details on their female participation and programs.
- **Support for STEM and future career choice** – Companies and industry associations offer support for students into STEM and the mining industry. Examples include the AREA Bright Future STEM Program that engages primary school students in Years 5–6 (AREEA, 2024), the CSIRO STEM Professionals in Schools national volunteer program (CSIRO, 2024) and NSW Minerals Council PRIME (Pathways to Resources Industry and Mining Engineering) Program for students in Years 9 and 10 as well as Careers Dinners program for Years 10, 11 and 12 students and parents (NSW Minerals Council, 2024).

WHAT NEEDS TO BE DONE? RECOMMENDATIONS

The industry does well in providing 'pink champagne and cupcake' opportunities but lacks national co-ordination especially in addressing the fundamental issues of gender diversity, equity and inclusion. The industry needs to move further beyond what the author terms 'pink washing' or the practise of promotion of gender diversity but not actually putting it into action.

Now is the time to the industry to walk the talk and focus on real solutions for our real problems.

Every company is unique, but every company can review and support gender diversity, equity and inclusion. Actions to progress gender parity could include establishing a clear company position; ensuring that this position is cascaded throughout the company with appropriate training; reporting and reviewing gender participation as well as supporting positive workforce initiatives and a positive culture with a people-centric issues reporting process. With the recently legislated positive duty for employers to prevent sexual harassment, this is the time for every company to review and reflect on policies and performance.

At an industry level, some clear issues or gaps that have been identified in the support to progress female participation in the minerals industry across Australia include:

- National organisation addressing structural challenges of gender diversity, equity and inclusion.
- National voice for women in mining.
- National co-ordination and collaboration of the different organisations that support women in mining and resources.
- National (or even state specific) 'one stop shop' for information and resources to support women in mining for companies and participants.
- Australian contact point for international liaison regarding women in mining.
- Perception of mining and the industry's suitability (and safety) for women.
- Broadscale mapping of company-based gender initiatives and promotion throughout industry.
- Co-ordination of promotion of the suitability of the minerals industry for women.
- Co-ordination of support for students (primary, secondary, tertiary including trades) to provide guidance on minerals industry career options and encourage the study of STEM.
- Sponsorship, mentoring and support for women in all career stages and to move to Executive/Board roles.
- Broadscale assessment and management of the 'leaky' pipeline of women leaving the industry, especially in childbearing years and beyond.

- Broadscale promotion of role models as '*you can't be what you can't see'.*
- National report on sector performance that would be an opportunity to measure, review, report then reflect and improve.
- Diversity and inclusion support beyond gender diversity.

Addressing these issues at a national level would support advancement of gender diversity and industry participation.

Understanding that a new approach is needed, leaders around Australia have recently come together to form a new independent organisation, Women in Mining and Resources Australia (WIMARA). The objective of WIMARA is to unite and connect stakeholders and initiatives to support women in the minerals and resources (including mining, renewables, oil and gas) industry across Australia. WIMARA is an independent, inclusive, not for profit organisation with the core purpose of supporting the attraction and retention of women in the minerals industry across Australia by addressing the challenges of gender inclusion and diversity. The aim of WIMARA is not to replicate or repeat other state-based or stakeholder activities but act to foster co-ordination, co-operation and collaboration between the different stakeholders and state or territory groups as well as amplify reach.

CONCLUSION

> *When it comes to gender equality, the mining sector has a tremendously wide gap to close* – World Bank, 2021

So, are we there yet? The data and statistics tell us that we have a long road to go, but at least we have an understanding of the journey needed to deliver the future workforce for the mining industry including the road ahead and some of the roadblocks.

The mining industry has made significant improvements in health and safety over the last decade, reducing the incidence rates of both fatalities and serious injuries. In the 12 years to 2015, the fatality rate in the mining industry decreased by 65 per cent from 12.4 fatalities per 100 000 workers in 2003, to 4.4 in 2015 (Safe Work Australia, 2024).

Now is the time for the minerals industry to do the same for gender diversity, equity and inclusion so take some giant leaps for womankind. With the current awareness and understanding, legal, moral and business imperatives, this is the time. The time for the minerals industry to act and lead. If not now, then when?

The future of the minerals industry is too important to ignore this call to action.

ACKNOWLEDGEMENTS

The author thanks her fellow champions of diversity and inclusion and those who listen, those who act, those who lead (and those who don't, and so make us stronger in our determination).

> *Life is not easy for any of us. But what of that? We must have perseverance and above all confidence in ourselves. We must believe that we are gifted for something, and that this thing must be attained.* – Marie Curie

For transparency, the author is Immediate Past Chair for Women in Mining Network NSW, (WIMnet NSW) and a leading member of the working group to develop Women in Mining and Resources Australia (WIMARA).

REFERENCES

AusIMM, 2024. AusIMM Diversity and Inclusion Survey 2024, The Australasian Institute of Mining and Metallurgy. Available from: <https://www.ausimm.com/news-and-media/ausimm-news/ausimm-diversity-and-inclusion-survey-2024/> [Accessed: 5 July 2024].

Australian Broadcasting Corporation (ABC), 2018. Women were only let into underground mines 30 years ago, so why are they leaving the industry?, 15 August 2018. Available from: <https://www.abc.net.au/news/2018–08–15/the-battle-to-keep-women-in-mining/10118930> [Accessed: 5 July 2024].

Australian Broadcasting Corporation (ABC), 2024. Cost of living crisis is unearthing more women who want to work in the mining industry, 22 April 2024. Available from: <https://www.abc.net.au/news/2024-04-22/cost-of-living-more-young-people-women-work-in-mining/103733692> [Accessed: 5 July 2024].

Australian Bureau of Statistics (ABS), 2021. Changing female employment over time. Available from: <https://www.abs.gov.au/articles/changing-female-employment-over-time> [Accessed: 5 July 2024].

Australian Bureau of Statistics (ABS), 2024. Gender indicators. Available from: <https://www.abs.gov.au/statistics/people/people-and-communities/gender-indicators#key-indicators> [Accessed: 5 July 2024].

Australian Government, 1998. Equal Pay Handbook. Available from: <https://humanrights.gov.au/sites/default/files/content/pdf/sex_discrim/equal_pay.pdf> [Accessed: 5 July 2024].

Australian Government, 2022. Respect@Work: Sexual Harassment National Inquiry Report. Available from: <https://humanrights.gov.au/our-work/sex-discrimination/publications/respectwork-sexual-harassment-national-inquiry-report-2020> [Accessed: 5 July 2024].

Australian Government, 2023. New workplace sexual harassment laws. Available from: <https://www.fairwork.gov.au/newsroom/news/secure-jobs-better-pay/new-workplace-sexual-harassment-laws> [Accessed: 5 July 2024].

Australian Institute of Management (AIM), 2024. The Business Case for Gender Diversity. Available from: <https://www.aimbusinessschool.edu.au/why-abs/blog/case-for-gender-diversity> [Accessed: 5 July 2024].

Australian Resources and Energy Employer Association (AREEA), 2024. Bright Futures STEM Program. Available from: <https://www.brightfuturestem.com.au/> [Accessed: 5 July 2024].

Australian Securities Commission (ASX), 2024. More women looking to build long-term wealth via ASX. Available from: <https://www.asx.com.au/blog/investor-update/2024/more-women-looking-to-build-long-term-wealth-via-asx> [Accessed: 5 July 2024].

Bank of America, 2024. The rising wealth of women, Bank of America Institute, 13 March 2024. Available from: <https://institute.bankofamerica.com/content/dam/transformation/rising-wealth-of-women.pdf> [Accessed: 5 July 2024].

BHP, 2020. Inclusion and Diversity: Partnering for Change. Available from: <https://www.bhp.com/careers/inclusion-diversity/storybook> [Accessed: 5 July 2024].

BHP, 2024. Case study: Bamboo flexible work crew. Available from: <https://www.bhp.com/news/case-studies/2024/04/bamboo-flexible-work-crew> [Accessed: 5 July 2024].

Cohen, D R, 2022. Australian Geoscience Tertiary Education Profile 2003–2021. Report to the Australian Geoscience Council. Available from: <https://www.agc.org.au/resources/reports/australian-geoscience-council-report/> [Accessed: 5 July 2024].

CSIRO, 2024. STEM Professionals in Schools. Available from: <https://www.csiro.au/en/education/programs/stem-professionals-in-schools> [Accessed: 5 July 2024].

Daniels, D P, Dannals, J E, Lys, T Z and Neale, M A, 2024. Do Investors Value Workforce Gender Diversity?, *Organization Science* (in press). Available from: <https://ssrn.com/abstract=4825030> [Accessed: 29 July 2024].

Elizabeth Broderick and Co, 2022. Report into Workplace Culture at Rio Tinto. Available from: <https://www.riotinto.com/-/media/Content/Documents/Sustainability/People/RT-Everyday-respect-report.pdf> [Accessed: 5 July 2024].

Elizabeth Broderick and Co, 2023. Report of the Expert Independent Review into Workplace Culture at Gold Fields. Available from: <https://www.goldfields.com/respectfulworkplace/en/downloads/gold-fields-EBCo-respectful-workplace-report.pdf> [Accessed: 5 July 2024].

Ernst and Young (EY), 2024. Top 10 business risks and opportunities for mining and metals in 2024. Available from: <https://www.ey.com/en_au/mining-metals/risks-opportunities> [Accessed 20 July 2024].

Gold Fields, 2023. Gold Fields 'deeply concerned' after report reveals toxic workplace bullying, sexual harassment, racism. Available from: <https://www.goldfields.com/in-the-news-article.php?articleID=13427> [Accessed: 20 July 2024].

Government of Western Australia, 2022. Western Australian Government response to the Community Development and Justice Standing Committee Report 2: 'Enough is Enough' Sexual harassment against women in the FIFO mining industry. Available from: <https://www.dmirs.wa.gov.au/sites/default/files/atoms/files/enough_is_enough_response.pdf> [Accessed: 5 July 2024].

Government of Western Australia, 2024. Mental Awareness, Respect and Safety (MARS) Program Initiatives. Available from: <https://www.wa.gov.au/system/files/2024-04/initiatives_2024.pdf> [Accessed: 5 July 2024].

Handley, H K, Hillman, J, Finch, M, Ubide, T, Kachovich, S, McLaren, S, Petts, A, Purandare, J, Foote, A and Tiddy, C, 2020. In Australasia, gender is still on the agenda in geosciences, *Advances in Geosciences*, 53:205–226. Available from: <https://adgeo.copernicus.org/articles/53/205/2020/> [Accessed: 5 July 2024].

Hunt, D V, Yee, L, Prince, S and Dixon-Fyle, S, 2018. Delivering through diversity. Available from: <https://www.mckinsey.com/capabilities/people-and-organizational-performance/our-insights/delivering-through-diversity#/> [Accessed: 5 July 2024].

Intergovernmental Forum, 2023. Women and the Mine of the Future, Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development. Available from: <https://www.iisd.org/system/files/2023-04/women-mine-of-the-future-global-report.pdf> [Accessed: 5 July 2024].

International Labor Organization (ILO), 2021. Women in mining: Towards gender equality. Available from: <www.ilo.org/publns> [Accessed: 5 July 2024].

KPMG, 2020. Establishing a new mining workforce. Available from: <https://assets.kpmg.com/content/dam/kpmg/au/pdf/2020/establishing-new-mining-workforce.pdf> [Accessed: 25 July 2024].

Minerals Council of Australia, 2024a. Trade and Investment: Investing in the Future. Available from: <https://minerals.org.au/policies/trade-and-investment/> [Accessed: 25 July 2024].

Minerals Council of Australia, 2024b. Respectful workplaces. Available from: <https://minerals.org.au/policies/safety-and-health/respectwork/> [Accessed: 2 August 2024].

NSW Government, 2024a. NSW Budget 2024–25 Gender Equality Budget Statement. Available from: <https://www.nsw.gov.au/sites/default/files/noindex/2024–06/NSW-Budget-2024–25-gender-equality-budget-statement-glossy-accessible_v2.pdf> [Accessed: 5 July 2024].

NSW Government, 2024b. Regulator intensifies efforts to combat psychosocial hazards and sexual harassment. Available from: <https://www.resourcesregulator.nsw.gov.au/news-articles/regulator-intensifies-efforts-to-combat-psychosocial-hazards-and-sexual-harassment> [Accessed: 5 July 2024].

NSW Minerals Council, 2024. Education and careers. Available from: <https://nswmining.com.au/education-and-careers/> [Accessed: 5 July 2024].

PriceWaterhouseCoopers (PWC), 2024. Global Workforce Hopes and Fears Survey 2024. Available from: <https://www.pwc.com/gx/en/issues/workforce/hopes-and-fears.html> [Accessed: 5 July 2024].

Rio Tinto, 2023. Women in Aluminium Program. Available from: <https://www.riotinto.com/en/careers/leadership-programs> [Accessed: 5 July 2024].

Safe Work Australia, 2024. Mining. Available from: <https://www.safeworkaustralia.gov.au/safety-topic/industry-and-business/mining> [Accessed: 20 July 2024].

Taylor, Z, 2016. A woman's place is in the mine, Curtin University. Available from: <https://www.curtin.edu.au/news/womans-place-mine/> [Accessed: 5 July 2024].

Whitehaven, 2022. Whitehaven employees set to enjoy industry-leading Paid Parental Leave Policy. Available from: <https://whitehavencoal.com.au/whitehaven-employees-set-to-enjoy-industry-leading-paid-parental-leave-policy/> [Accessed: 5 July 2024].

Workplace Gender Equality Agency (WEGA), 2019. Gender equitable recruitment and promotion, August 2019. Available from: <https://www.wgea.gov.au/publications/gender-equitable-recruitment-and-promotion> [Accessed: 5 July 2024].

Workplace Gender Equality Agency (WEGA), 2023. Australia's Gender Equality Scorecard, November 2023. Available from: <https://www.wgea.gov.au/sites/default/files/documents/WGEA_Gender_Equality_Scorecard_2022–23_0.pdf> [Accessed: 5 July 2024].

Workplace Gender Equality Agency (WEGA), 2024a. Employer Gender Pay Gap Snapshot, 27 February 2024. Available from: <https://www.wgea.gov.au/sites/default/files/documents/Employer%20Gender%20Pay%20Gaps%20Snapshot_FINAL_1.pdf> [Accessed: 5 July 2024].

Workplace Gender Equality Agency (WEGA), 2024b. WEGA Employer of Choice for Gender Equality Citation Holders, 30 July 2024. Available from: <https://www.wgea.gov.au/what-we-do/employer-of-choice-for-gender-equality/current-eocge-citation-holders> [Accessed: 1 August 2024].

World Bank, 2021. Impactful Women – Examining opportunities and constraints for women in mining organizations worldwide. Available from: <https://www.worldbank.org/en/events/2022/02/10/ImpactfulWomenReportLaunch> [Accessed: 6 July 2024].

World Economic Forum (WEF), 2024. Why gender inclusion is an imperative for future-ready workplaces. Available from: <https://www.weforum.org/agenda/2024/03/why-gender-inclusion-is-a-imperative-for-future-ready-workplaces/> [Accessed: 1 August 2024].

Effects of the green transition on miners' work, competencies and skills

A Pekkari[1], J Johansson[2], E Lund[3] and J Lööw[4]

1. PhD student, Luleå University of Technology, 977 54 Luleå, Sweden.
   Email: annika.pekkari@ltu.se
2. Professor, Luleå University of Technology, 977 54 Luleå, Sweden. Email: jan.johansson@ltu.se
3. PhD student, Luleå University of Technology, 977 54 Luleå, Sweden. Email: erik.lund@ltu.se
4. Associate Senior Lecturer, Luleå University of Technology, 977 54 Luleå, Sweden.
   Email: joel.loow@ltu.se

EXTENDED ABSTRACT

Technological development is accelerating in the mining industry (Abrahamsson and Johansson, 2021) and in large parts of the world there is an increased environmental awareness (United Nations, 2015). This can mean both challenges and opportunities. The mining industry has long been criticized for its adverse environmental effects. However, there is now a lively discourse about the role of mining in facilitating the green transition towards sustainable development. Mining is increasingly recognised as a prerequisite for the green transition, by supplying key raw materials to enable, for example, digitisation and batteries for electric vehicles. The green transition not only amplifies the demand for metals and minerals but also intensifies pressure on the mining sector to assume greater responsibility for environmental and societal welfare (Dehaine *et al*, 2020). New technology, such as digitisation, automation, and remote control, play a crucial role in advancing towards more sustainable mining practices. Despite the expanding role of advanced technology, human involvement will remain important in the extraction process (Rogers *et al*, 2019), but new technology will change how miners do their work, which in turn will lead to changed competence requirements for miners (Herbert and Hidalgo, 2021) and increased need for further education. Given the significant shift towards sustainable mining, it is important to study how these changes may affect the work, competences, further education and skills of miners as human expertise will continue to be critical in the extraction process. Consequently, there is a need for proactive research to prepare for the inevitable changes and implement measures to support miners through this changeable period to ensure a smooth transition that protects miners' safety and working environment. This extended abstract explores how new technology will affect the need for further education of miners in the future.

METHOD

The results are based on exploratory and qualitative methods and theoretical analyses of two separate studies. The first study was a web-based survey with 21 questions with both fixed and open answers distributed to technology and organisational experts participating in an EU project on the next-generation mining equipment (*Nexgen Sims*). The project included 12 EU countries and Australia. The experts consist of HR personnel, managers, executives, engineers, geologists, and academics involved in or associated with mining operations. The purpose of the survey was to examine how the green transition will affect mining over the next decade by examining the experts' future visions for the mining industry as their perceptions should influence the future, as they work to develop future mining technology and mining work. Therefore, their visions of the future will likely shape the trajectory of mining development and organisational practices. Despite a relatively modest response rate of 44 completed surveys, the results offer valuable insights of how these technology and organisation experts perceive prevailing and future trends and patterns within the mining industry, due to the green transition. The results of the open-ended responses were analysed thematically and the responses with fixed response options were compiled into diagrams. There were 33 men and 11 women who participated in the study, of which 43 of them work within the EU and one person works in Australia. This means that the result is not transferable to a larger population, but the result reflects the perceptions of these respondents. The second study was conducted through six workshops with miners, production managers and human resource personnel within one Swedish mining company. In the study, 43 employees participated, of which 28 persons were men and 15 persons were women. During the workshops, participants were able to reflect and discuss their thoughts on threats and opportunities regarding new technology, learning and further education in the mining industry in general and for miners in particular. During the workshops, what the participants said was written down. The text was later coded with keywords and the keywords were then collated and organised to form overarching themes that were analysed.

RESULTS AND CONCLUSIONS

The results of both studies underline the significant role the new technologies, especially digitisation, automation and remote control, have for the green transition. Both studies highlight that there will be a constant stream of new technology in the future, that will change the tasks and working conditions of miners. According to the workshop results, the new technology will require an increased demand for continuous further education among miners, to be able to handle the new technology and perform their work. The workshop results show that mining employees consider further education as a natural part of the work and that all miners must continuously develop their competences and skills to be able to carry out their work. At the same time, the results of the survey study show that most of the technology and organisational experts (57 per cent) believe that miners' lack of willingness to be further educated is the biggest challenges regarding further training of already employed miners over the next 10-year period. The different perceptions of miners' willingness to further education, as these studies suggest, could have major consequences for miners' working conditions. If technology developers believe that miners are not willing to learn new technologies, this may lead to the design of new technologies not taking sufficient account of miners' needs and abilities or not provide adequate documentation, training materials or support. Miners who feel that their need and willingness for further education is not taken seriously can lead to frustration, dissatisfaction, lower work morale and higher staff turnover.

Despite the insights contributed by these two studies, their limited scope is a factor that prevents the results from being generalised to the entire mining industry. To draw more robust and transferable conclusions, it would therefore be of great interest to carry out further research in this area. Larger studies with wider samples could provide a more representative picture of how new technology affects work tasks and further education needs of miners. Furthermore, more extensive research could identify specific barriers and opportunities for further education, which would be invaluable in developing effective training strategies and support measures for miners.

REFERENCES

Abrahamsson, L and Johansson, J, 2021. Can new technology challenge macho-masculinities? The case of the mining industry, *Mineral Economics*, 34(2):263–275. https://doi.org/10.1007/s13563-020-00221-8

Dehaine, Q, Michaux, S P, Pokki, J, Kivinen, M and Butcher, A R, 2020. Battery minerals from Finland: Improving the supply chain for the EU battery industry using a geometallurgical approach, *European Geologist*, 49:5–11.

Herbert, J and Hidalgo, A, 2021. Improving the engineering education in the raw materials sector in an advanced, decarbonised, and digital European society, 21st International Multidisciplinary Scientific GeoConference SGEM 2021.

Rogers, P W, Kahraman, M M, Drews, F A, Powell, K, Haight, J M, Wang, Y, Baxla, K and Sobalkar, M, 2019. Automation in the Mining Industry: Review of Technology, Systems, Human Factors, and Political Risk, *Mining, Metallurgy and Exploration*, 36:607–631. https://doi.org/10.1007/s42461-019-0094-2

United Nations, 2015. Paris Agreement [online]. Available from: <https://unfccc.int/process-and-meetings/the-paris-agreement> [Accessed: 16 July 2024].

Incorporating controls and automation into mining engineering curriculum

S J Schafrik[1] and M Long[2]

1. Associate Professor, University of Kentucky, Lexington, KY 40506, USA.
   Email: steven.schafrik@uky.edu
2. Associate Professor, University of Kentucky, Lexington, KY 40506, USA.

ABSTRACT

There are several factors that are increasing the need for new graduates to be ready to design and manage more autonomous operations at mines. Autonomous controls and systems range from the start-up, control, and shutdown of processing plants to the autonomous operation of vehicles. These operations require the workers, engineers, and management to have additional skills for programming, debugging, tasking, and maintaining the equipment. The future survivability of many mining operations will be influenced by a company's willingness and ability to understand, accept, and utilise this technology for safe and productive operations. This is an educational opportunity and challenge that needs to be addressed throughout the student's experience, from first year to graduate level. This paper discusses the lessons learned from a decade of multidepartment effort at all student levels and many courses that are able to incorporate data science, controls, and autonomous design into the already topic-rich national curriculum. This approach also exposes other engineering disciplines to the mining industry which is a valuable recruiting tool for talent outside of the mining engineering departments.

INTRODUCTION

Modern mining machines are closer to robots than to earth moving vehicles. The mining industry's push to automation over the past few decades has changed the mission of the engineers and technicians. Engineering students who are aspiring to work in maintenance or in production need to be familiar with the hardware and software that is used to automate the equipment. Several universities across the world have built automation labs to teach PLC programming to students and professionals.

The training materials available from the manufacturers focuses on the PLCs capabilities and the functions that are available. The study guide provided by Rockwell Automation, the manufacturer of Allen Bradley PLCs, is in multiple modules. The first module is all about the physical connections on the machines, how to interface a computer with it, and how to install their software. The second module starts with a simple program. The rest of the second module introduces particular PLC instructions. The introduction of the instruction is accompanied by an exercise using the new instruction (Rockwell Automation, 2011a, 2011b). This is a traditional education approach: introduces a new concept and supplies problems that use that new concept to reinforce the learning.

When training practicing and aspiring engineers, this traditional approach can be too slow for the audience. Training that is outside of higher education and targeted at professionals who want to learn to program are taking a different approach. This training is starting to take advantage of the concept of patterns of programming. This approach assumes that the student can understand not just the instructions but also how the instructions interact. Teaching using patterns of programming also allows students to jump immediately into real-world examples without having to spend time on each and every instruction. Placing the emphasis on the pattern allows students to learn acceptable standards and practices at the same time as learning the mechanics of the language. Training in the use of programming patterns will be essential for new graduates. The use of modular sets of programming patterns has become extremely common in real use cases as outlined by Neumann *et al* (2020). The structure and readability of an individual code is important to the students' understanding but also for providing readability to their code. Students can have a wide range of code structure and readability with the quality of a student's programming structure being a major determinant of their success in a course (Nurollahian *et al*, 2024). Programming patterns can provide a standardised structure of PLC programming and as such aid in the students understanding with the course and success in real use cases when collaborating.

This discussion will be around ladder logic programming. It is assumed that a Rockwell Studio compatible language will be used, although programming patterns are generalisations and intended to be applied in multiple specialised cases.

A common example of a specialised programming pattern in the real world is the adapter. The adapter pattern arises from differences in interface inputs and outputs. Similar to using a three prong plug with and a two prong outlet. Should you want to plug the three prong plug into a two prong outlet an adapter would be needed. An example is an alarm that will be set off at certain percentages for a vehicle's fuel level. The float sensor in the vehicles tank provides readings in voltage. The sensor and alarm are not compatible as one outputs voltage and the other reads percentage. The simple solution is to transform the voltage reading into a percentage reading. By knowing the max and min voltages of the float sensor we can determine the percentage of the tank's fuel level from the instantaneous voltage. That act of using an intermediate converter is the adapter programming pattern. While this was a very simple example there are adapter designs that can be much more complicated. Some adapters need to transform multiple different inputs into a single output type. In reality this more complicated programming pattern can be broken back down into multiple simpler parallel adaptors. Adapters that require multiple transformations can also be broken down into multiple simple adaptors in sequential series.

The most commonly used language used in Rockwell Studio is ladder logic. Ladder logic uses rungs which are analogous to lines of code or rules. The rungs are read sequentially top to bottom and within each rung they are read left to right. Once the program has processed the bottom rung it will return to the first rung and begin again in a continuous loop looking for any changes. The program constantly does this many times per second providing near immediate execution.

Ladder logic can be read similarly to an electrical diagram. Each rung has at least one contact and one coil. When a contact or contacts are closed or activated the circuit is completed and any downstream coils are energised. The contacts are the inputs on the rungs with the coils being the outputs. Rungs can have many other components such as memory instructions, math instructions, or inequality instructions. The interaction between inputs is interpreted using Boolean logic. Looking below at Figure 1 an example of an AND circuit is shown in ladder logic. In order for the Output to be energised both Input 1 and 2 must be closed. In Figure 2, the Output can be energised by either Inputs 1 or 2 as there is a bypass in the circuit, this is an OR circuit. All Boolean logic in ladder logic is combinations of these programming structures.

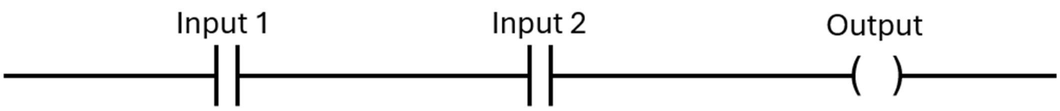


FIG 1 – Ladder logic AND example.

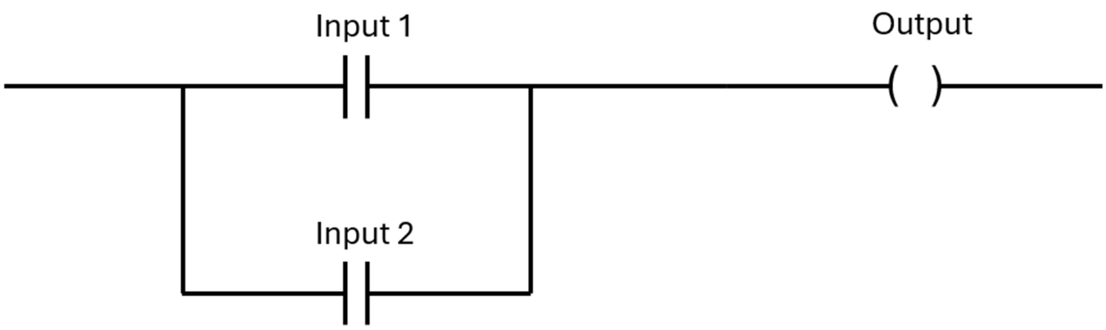


FIG 2 – Ladder logic OR example.

At the University of Kentucky we have built spaces for teaching within the research labs. Computers installed with Rockwell Studio are provided for students for use during class and for assignments. Connected to the computers are training panels with buttons, dials, and switches to imitate real life control panels. To simulate the real life outputs a number of motors with VFD control or direct control are available for use along with a water tank flow system with pumps and proportional control valves. For more advanced studies a standard robotic arm with six degrees of freedom is set-up to use as well as a hydraulic system similar to the example described below. The conjunction of both the programming availability and physical outputs allows for students to see real time results of their programs. These physical results not only provide real time feedback but the equipment used was chosen to be similar to real world examples. Creating real world challenges for the students not only motivates them to learn more (Zamora-Hernandez, Rodriguez-Paz and Gonzalez-Mendivil, 2023) but can also prepare them for situations they may face in their future careers.

EXAMPLE

When teaching automation of any sort, it is important for the students to understand the physical connections that will be made in the automation system. Engineering education traditionally teaches mechanical connections, with the students getting that information in Engineering Mechanics classes, such as Statics and Dynamics. Automation systems in the mining industry will most often be a combination of mechanical, hydraulic, and electrical systems. Each of these subsystems has their own designs and impact on the other systems.

The following sections of this paper will present some programming patterns that work with an example machine. The example machine is intended to move a cutting tool such as a water jet to cut stone. It has an electric-driven hydraulic spool valve controlling a double-action hydraulic cylinder driving a four-bar linkage until it triggers non-contact proximity switches at particular locations. The programmer needs to be able to break the system down into the subsystem components in order to understand the potential for failures and goals of each subsystem. The mechanical system alone may consist of the connection bars, bearings, fasteners, and positioning bolts that trigger the non-contact proximity switches. Over time, bars can bend, bearings wear out, and positioning bolts loosen. However, this moving system can also cause wear on wiring and hydraulic hoses. Crashes of the system can damage or move the switches and be dangerous to anyone around the machine. The autonomous control of the hydraulic system may also require the control of the hydraulic pumping system or monitoring the pressure available to the cylinder. The control needs to monitor the position switches and react to the movement accordingly. If humans are expected to be working in proximity to the mechanism, there needs to be a way to alert them to the autonomous movement.

With the student's understanding of the physical apparatus in place they are ready to start understanding the programming patterns that can be used to control it.

Captive signals

The captive signal programming pattern is generally the first programming pattern students are taught. It is also one of the most useful programming patterns, especially for using Boolean logic in programs. The captive signal pattern takes in an input, energises, and outputs and will keep the output energised until another signal interrupts the signal. The pattern reads: if the signal is received or the output is on and the interruption signal is not received, then turn on the output. An example of a captive single is shown in Figure 3.

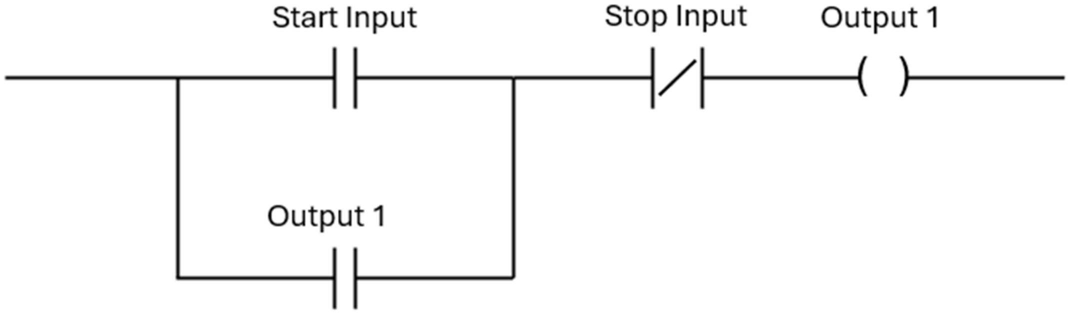


FIG 3 – Captive single ladder logic example.

This is the programming equivalent of a magnetic on-off switch. It demonstrates to the student that they can check that outputs are energised the same as inputs and also it demonstrates the momentary nature of the PLC's scan rate. Students who have taken procedural programming or object-oriented programming will be accustomed to setting a variable and that variable remaining set until changed. In PLC programming, the current state of the entire program is evaluated on every scan of the PLC. This means the physical state of the equipment has a lot of influence on the state of the variables.

Many PLCs are capable of using a Latch/Unlatch instruction. These two instructions can be used on two rungs to accomplish similar results in many cases. However, these instructions may be able to survive a power cycle and may cause a machine to be energised on start-up and should not be used for on-off switching. These instructions are very useful for setting Boolean variables.

In the example mechanism, a hydraulic pump is necessary to power the piston. Before any piston moves can be commanded then the pump must be on. Using a captive signal pattern, on, off and emergency stop inputs or buttons can be added to the system with simple wiring and simple programming.

The flip-flop

There are several different names for the type of circuit that will take a single input and will either swap an output on or off or reverse polarity. This is normally in commercial applications a single on-off button as opposed to the on-off mechanism described above. In industrial applications the users often want a single button to control the behaviour of a mechanism. This is not limited to buttons, a single input would flip a mechanism from the current setting.

This pattern requires two rungs. The first rung reads: if a signal is received, energise a one-shot instruction and energise the stored output. The second rung reads: if the stored output is energised and not the output is energised or not, the stored output is energised, and the output then energises the output. An example of a Flip-Flop Circuit is shown below in Figure 4. The difference between this and the captive signal is the addition of a variable for the stored output. The one-shot instruction works for one cycle of the PLC only, which allows this logic to work.

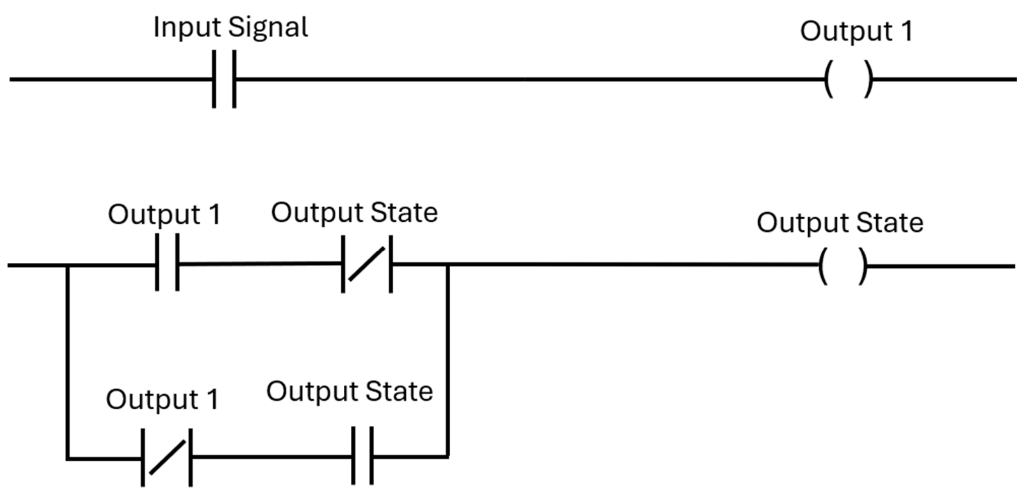


FIG 4 – Flip-flop circuit example.

In the example mechanism, the flip-flop programming pattern can be used to reverse the direction of the piston when a limit switch is triggered. This could be done with the switches wired together, as one signal or as separate signals with either energising the one shot instruction.

Timers

Timers are useful for many different applications and they are the programming version of a timer relay. In mining applications timers are extremely useful in start-up operations. Many mining machines require a high start-up amperage and starting many machines at once will be a large spike.

Starting machines in a cascade is straightforward using the captive signal pattern with an additional trigger from a timer.

PLC languages generally have count-up or count-down timers. Count-up timers are normally used where they are energised by a signal and time how long the signal has been energised. There will be a separate timer reset instruction that can reset the timer when necessary for the application. Count-down timers typically must be energised with a captive signal pattern. When the timer is done, the timer done instruction or bit is used as the stop in the captive signal.

The purpose of the timer programming pattern is to show how bits or sub-parts of complex PLC variable types can be used within the patterns already presented.

In the example mechanism, the timer has multiple uses. A count up timer could be used to time the amount of time that the hydraulic pump is energised and a separate timer to count the amount of time that the hydraulic cylinder is running. The system designer could manually run the cylinder in all directions and determine the amount of time it typically takes to go from one position to another. A set of count-down timers could be established so that when a command to move is initiated the cylinder will move and approach the proximity switch at the location. The end of the timer could be used as a captive signal to continue moving the cylinder, at a lower speed, until the proximity switch is triggered. In this way, the two patterns can be combined.

Single button selection

In many applications, it's desirable to have a single button that is used to set the level, location, or speed of another control. For example, many space heaters have one button that is used to set several temperatures.

The purpose of the single-button selection programming pattern is to demonstrate math and logic instructions. On the first rung, energising the button will activate an add instruction changing a variable that stores the state of the mechanism. On the second rung, a greater than or equal to instruction will trigger a move instruction to reset the state of the mechanism when the greatest number of modes is exceeded. On separate rungs for the individual actions, equal instructions can be used to energise the desired commands.

In many PLC languages, this kind of programming pattern is called a State Machine and will have a particular syntax for that instruction.

In the example mechanism, a button can be added to move the mechanism from one predefined stop point to the next. As each mode is energised the timer pattern can be implemented to perform the action, but it's triggered on the single button selection. In this way, the movements of the mechanism are regular, not allowing the user to select a desired location, they can only go from one location to the next.

Analogue control

All the patterns presented so far are Boolean patterns, meaning they are all on or off. Many sensors and many controls use analogue signals. Those signals could use voltage or amperage to communicate. From the typical PLC program, it is set-up from the input or output module and only the signal itself is available to the program. Mechanisms and programs that are connected mostly to analogue devices will often use the move instruction. Analogue inputs are best read on rungs after a move command puts the current analogue signal into a variable (ie tag). Subsequent actions should be performed on that variable instead of on the hardware's value to avoid accidental memory collision between the program and the analogue modules. For debugging purposes, the programmer can set the level from a constant. Analogue output is done in the exact opposite direction, a move command is used to place the signal in the memory of the output hardware.

In the example mechanism, analogue knobs could be used to adjust the time that the cylinder will be contracted or extended. The reading from the knob could be normalised and used as the time value on the timer. This will allow the user to move the mechanism to a stop point between the proximity sensors.

Example application, PID control

The example mechanism as described will operate but will not be optimised. Controlling machines using only the previously described programming patterns will operate but is not taking advantage of the computing capability of the PLCs. Particularly the ability to do programmable a proportional-integral-derivative (PID) control. PID control is common on industrial machines and is used to approach a constant variable setting (eg temperature, speed, or water level). Many modern PLC implementations have a PID or a PID (PID Enhanced) instruction, while formerly the math involved in the PID calculation had to be manually coded. PID implementations are software and version-specific but are normally just a combination of the captive signal and timer design patterns.

In the example mechanism, a PID control could be used to control the hydraulic spool valve's position to get a consistent speed between set points. This will appear to the user like a soft start mechanism for the machine. The hydraulic pump could be powered by a variable frequency drive (VFD) and the PID used to control the pump based on the movement command for the mechanism.

COURSE INTEGRATION

Educators should integrate programming patterns into their curriculum to prepare students for the increasing demands of designing and managing autonomous operations in mining. A holistic engineering curriculum view should be taken as opposed to an individual class-based view. Students have been introduced to programming patterns in their introductory classes and mastery of their usage is practiced through to post graduate classes. In their first semester, students are taught the programming patterns for sensor interfaces, eg how to read data from a sensor and use it to cause a desired effect. An example of this is a rudimentary temperature gauge, where a thermocouple provides a voltage reading that can be used to determine temperature. Then, the students use this reading to move a motor to physically represent the temperature on a gauge. This is further compounded in a subsequent course, in which a sensor is used to control a motor. This project required a complex sensor reading from image processing and the movement of multiple motors based on the readings to strike a target. The patterns is continued in the automation PLC course, utilising many of the patterns taught in earlier courses while introducing new patterns. By looking across courses rather than on a course-by-course basis, patterns of programming can be introduced early and mastered in later classes. This also provides more time to introduce patterns that build on each other and demonstrate the interaction between pattern systems. The programming pattern is far more useful for the students to understand than the specific solution, as the patterns can be applied to many more situations as they are not case-specific. By teaching students this approach to problem-solving, they can identify patterns and gain an understanding of what is required to perform that task. This provides students with a better understanding of how to approach problems they face in the field than a solution-specific approach.

To apply this across departments, the University of Kentucky has taken an approach that can be replicated. A student's introductory courses introduce universal patterns of programming; these are often very simple and common patterns. Next, the compounding of patterns by projects and assignments that require multiple patterns or more complex patterns to interact with each other is introduced. Finally, in a student's more specialised classes, more complex patterns can be introduced, and how to modify the solution structures to their needs. It is not feasible to cover every relevant programming pattern. However, patterns can be far more applicable across the board to students in their careers than solution-specific teaching. Programming patterns provide a methodology for problem solving rather than a few specific programming tools, eg a programming language or automation hardware platform.

CONCLUSIONS

Teaching a new programming language is difficult due to the depth and wide variety of problems that can be encountered. To tackle this problem and provide efficient teaching to new graduates and students a focus on programming patterns can be taken. This paper presents multiple types of programming patterns that can be used in the teaching environment. These patterns are extremely common in the field such as the captive signal or Flip-Flop design which provide effective solutions to controlling if a machine or process is on or off. Should students be required to program PLCs they will most definitely encounter one of the common programming pattern problems. So rather than a complete focus on the specifics of each part of the program, students can be taught to identify these common patterns. Once the individual identifies the pattern, they can then apply the solution structure as they were taught. No solution will fit every problem but by also teaching how to modify these solutions students can be given a wide tool belt of solutions that they can more easily apply to real world applications rather than building from scratch.

Automation in the mining industry is a way to attract talented engineering students. While other automation technology platforms, such as drones, are part of everyday life students see the potential for industrial applications. The automation described here is the beginning of doing the data collection necessary for artificial intelligence applications. Programming that has a tangible impact on the real-world is the goal of automation.

ACKNOWLEDGEMENTS

The work and insights in this paper could not have been done without the work of Drs Thomas Novak, Gerald Luttrell, and Mr Robert Bratton.

REFERENCES

Neumann, E-M, Vogel-Heuser, B, Fischer, J, Ocker, F, Diehm, S and Schwarz, M, 2020. Formalization of design patterns and their automatic identification in PLC Software for Architecture Assessment, *IFAC-PapersOnLine*, 53(2):7819–7826.

Nurollahian, S, Rafferty, A N, Brown, N and Wiese, E, 2024. Growth in knowledge of programming patterns: A comparison study of CS1 vs, CS2 students, *Proceedings of the 55th ACM Technical Symposium on Computer Science Education,* vol 1. https://doi.org/10.1145/3626252.3630865

Rockwell Automation, 2011a. RSLogix™ 5000 Level 1: ControlLogix System Fundamentals.

Rockwell Automation, 2011b. RSLogix™ 5000 Level 2: ControlLogix System Fundamentals.

Zamora-Hernandez, I, Rodriguez-Paz, M X and Gonzalez-Mendivil, J A, 2023. An educational model for teaching plc programming incorporating Soft Skills, The 15th International Conference on Education Technology and Computers. https://doi.org/10.1145/3629296.3629342

Virtual mine geologist – who needs a real one when AI can do the job?

S Sullivan[1]

1. Technical Lead, Maptek for DomainMCF, Adelaide SA 5065.
   Email: steve.sullivan@maptek.com.au

EXTENDED ABSTRACT

The key skills for a competent geologist are observation, documentation, analytical thought and the ability to communicate. These attributes have served the geological world for the past two centuries since the field of geology was separated out from natural philosophy. The understanding of the structural setting, lithologies, alteration and 3D distribution of the target mineral species are essential precursors to resource evaluation and potential economic extraction.

The advent of artificial intelligence and machine learning has matured to the point where observation by dedicated sensors and analysis by customised AI algorithms can replace manual processes and deliver credible results. In combination with analytical data such as assays, various sensors now collect physical properties of rocks which are used as proxies for mineral identification and rock mass classification. These sensors include X-ray and infra-red spectra, magnetic susceptibility, gravity/density, EH/pH measurements, conductivity, colourimetric readings, porosity, fracturing and fracture intensity.

Analysis using machine learning techniques trained using known data sets can determine rock type classification, rock density, quantification of grade/quality attributes, mineral alteration, weathering and geotechnical attributes such as rock quality. This type of data relies on calibration and quality control of a variety of different types of electronic hardware. The resulting data is non-additive, has error ranges and will be suitable for consumption by fast AI methods providing probabilistic analysis. A second stage could include geometallurgical constraints to provide an 'extractability index', which is of more interest to miners than pure geotyping. Using resultant interpreted geological criteria, 3D domain models with spatial attributes will be built.

In addition, advanced AI technology will replace traditional estimation techniques for interpolating grades between measured data. Conventional estimation for a single variable into a single geological domain using the inverse distance technique entails up to 190 decisions. Likewise, applying ordinary kriging to a single variable/single domain requires up to 170 decisions in preparation work alone, to determine appropriate parameter settings using variography and kriging neighbourhood analysis, followed by a further potential 220 decisions to carry out the kriging estimate.

Deposits rarely have a single commodity of economic interest within a single uniform geology. For a large multicommodity deposit it is realistic to have over 1000 variable/geological domain combinations. Applying kriging to estimation of the entire deposit requires around tens of thousands of decisions. Little wonder that establishing a conventional ore resource report involves weeks or months of geological effort. Time constraints often do not allow the competent person responsible for the resource reporting process to validate each and every decision. AI will provide rapid, auditable and easier workflows for the resource geologist.

CASE HISTORY OF WHAT IS AVAILABLE NOW WITH AI

Havilah Resources is an exploration and mining company focused on projects in the north-east of South Australia.

Mutooroo is a high-grade open pit and underground copper-cobalt-gold project located 40 mins west of Broken Hill. The host rocks at Mutooroo are high-grade metamorphics with sulfide mineralisation lying in a shear zone either within amphibolite or at the gneiss contact. The Mutooroo copper-cobalt ore is a coarse grained, massive sulfide comprising pyrrhotite, chalcopyrite, pyrite and barren quartz.

The current resource at Mutooroo is defined by 300 drill holes, including some diamond drilling by Broken Hill South Limited in the 1960s. Samples used for resource estimation came from diamond drill core and reverse circulation drilling. Exploration data analysis, variography, block model creation, grade estimation and block model reporting were completed using conventional techniques.

With the upsurge in the accessibility of artificial intelligence (AI), Havilah Resources applied the method to target downdip extensions to their copper-cobalt mineralisation.

The Mutooroo drill hole data and topographic surface information were uploaded to the Maptek DomainMCF application and a model was generated within the region defined by the extents of the resource block model. The resulting 3D lithological model shows the complex interaction between the host amphibolite and the sulfide vein lenses.

The next step was to model the copper mineralisation in more detail. Within the database, an indicator was established for samples grading more than 1000 ppm copper. This copper indicator was then modelled using the DomainMCF cloud compute service. The machine learning application analysed the copper indicators and their spatial distribution in 3D and provided projections for potential extensions to mineralisation. Solid wireframes of the DomainMCF copper indicator were generated in Vulcan.

Late in 2023, a drill program commenced to target the AI-generated extensions to mineralisation and successfully intersected copper-cobalt mineralisation close to the depths indicated by the AI model. Remarkably, it predicted in advance the presence of comparatively thick hanging wall mineralisation reported from the above drill holes, which was not immediately obvious from conventional geological interpretation. The DomainMCF model was updated as preliminary results were confirmed using pXRF results.

'*The machine learning model can be refreshed in minutes and so the geological/mineralised model is always up to date with the latest results*' said Chris Giles, Technical Director, Havilah Resources.

FUTURE ADOPTION OF AI AND THE VIRTUAL GEOLOGIST

The mine or resource geologist will change roles from a primary data collector and interpreter to that of a system integrator and/or data/process manager. The workflow and calibration of the sensors and machine learning algorithms will control this data-driven world. Benefits include automated data validation, auditable processes, consistent outcomes and integration into the digital mine platform.

Further afield in a non-invasive mining operation, pinpointing accurately the location of elements of interest will be critical, as there is no scope for adjusting the 'grade control' plan. AI will be the geologist's key tool for understanding and managing the extraction of mineral resources into the future.

Future skills and workforce evolution – training and skills development for mining operation engineer and drill and blast engineer in surface mineral mine PT Indo Muro Kencana

H Utama[1] and R Heryadi[2]

1. Junior Manager Mining, PT Indo Muro Kencana (PT IMK), Mt Muro Gold Mine, Central Kalimantan 73961, Indonesia. Email: heru.utama@imkgold.co.id
2. Lecturer, Nusa Putra University, Sukabumi, West Java, Indonesia. Email: rudy.heryadi@breny.my.id

ABSTRACT

PT Indo Muro Kencana (PT IMK) is a surface gold and silver mine located in Mt. Muro area, Central Kalimantan province, Indonesia. The mining operations of multiple open pits using combination of excavator and haul truck is operated. This operation is performed in two shifts in a day. The articulated dump truck (ADT) with capacity of 40 t and 60 t deliver ore to the mineral processing plant and discard waste material to the waste dump area. Overall, PT IMK's mining operation department is consisting of two sections, namely mining operation section and drill and blast section. Firstly, mine operation section is responsible to manage loading, hauling, pit service (mine dewatering, earthwork, road maintenance) and mine operation engineering. Secondly, drill and blast section is in charge to manage drilling and blasting (blast engineering, blasting operation, explosive permit and magazine or explosive storage). Additionally, conventional blasting method (ore-waste blasting) with non-electric initiation system is used and sleep blasting is undertaken as bulk explosive is buried for maximum two days. The first purpose of this paper is to elucidate about role of mining engineer in mining operation department (mining operation engineer and D&B engineer). At this point, mining operation engineering practice (fleet management system, production control and mining manpower management) and also blasting daily practice will be elucidated. Daily blasting practice is consisting of surface blast design, explosive engineering, sleep blast practice and the concept of scaled depth of burial to ensure a safe work environment in blasting activity. Next, the second purpose of this paper is to explore workforce evolution and future skills for mining engineer in surface mining operation. Furthermore, strategy to advance future skills such as mining continuous improvement program, training and skills development for mining engineer (mining operation engineer and D&B engineer) in order to develop their skills is also discussed. It is expected that in the future, these future mining leaders will become new mining leader, for instance mining superintendents, D&B superintendents and mining managers. In conclusion, it is clear that awareness about workforce evolution, professional development, training, skills development, mining economics awareness and mining continuous improvement program are essentially required as professional development for mining engineer (mining operation engineer and D&B engineer), in order to be commercially competitive in their future career and in order to be adapted with future workforce evolution in mining.

INTRODUCTION

Today, common mining practice of surface mineral mining operations in Indonesia is multiple open pits operation using combination of excavator and haul truck (articulated dump truck). In addition, articulated dump truck or ADT is operated to deliver ore to the mineral processing plant and also to discard waste material to the waste dump area. Also, mining operation activity is generally operated in two shifts in a day and conducted by mining operation department. Initially, the focus of this paper is to elucidate the role of mining engineers in surface mineral mining operation. The first purpose of this paper is to explain about the role of mining engineer in mining operation department, focus on mining operation engineer and drill and blast engineer. Furthermore, mining operation engineering daily practice, such as fleet management system, production control and mining manpower management will be discussed. Next, daily blasting practice and blast engineering, such as surface blast design, explosive engineering, sleep blast practice and the concept of scaled depth of burial also will be elucidated. Moreover, in order to ensure a safe work environment in blasting activity and also to support safety in mining operation, it is recommended that the concept of scaled depth of burial and sleep blast are combined and applied in blasting practices. Next, the second purpose of this paper is to describe workforce evolution and future skills for mining engineers in surface mineral mining operation, especially for mining operation engineer and drill and blast (D&B) engineer. It is expected that skills development, training, professional development program and also mining continuous improvement program can be conducted in order to develop their technical skills (hard skills) and soft skills. Next, it is projected that in the future, these young mining leaders will become future mining superintendents and mining operation managers.

THE ROLE OF MINING OPERATION DEPARTMENT IN SURFACE MINERAL MINING OPERATION

Initially, mining operation department is one of the core departments in a surface mineral mining. In PT IMK, it can be said that the other core departments are processing plant department, mine workshop department (mobile maintenance plant department) and mine geo services department (technical services department). Additionally, mining operation department is consisting of two core sections, namely mine operation section and drill and blast section. Firstly, mine operation section is responsible to conduct loading and hauling activity, pit service (mine dewatering, mine earthwork, road maintenance) and to conduct mine operation engineering (fleet management system and manpower arrangement of mining operator). In addition, safety excellence, operational excellence and financial excellence are the common key performance indicator (KPI) of mining operation department. Additionally, in term of financial excellence, it can be said that fuel usage (diesel fuel) for mining operation's units and all mining cost of operation activity is the important component of financial excellence. At this point, it is said that mining operation department is responsible to conduct daily mining operation activity, to manage safety in mining operation, to control operational and to organise related mining activity. Next, it is noted that these activities are conducted by mining operation department: land clearing, bench preparation, top soil removal, waste loading, ore loading, mine blasting (ore and waste), hauling (transport) of waste rock and ore minerals (ore is transported to ROM pad at processing plant area and waste rock to waste dump area), mine support activity such as drill blast area preparation, highwall sloping, pit service, special project of mine blasting (secondary blasting, special drilling and blasting project). Also, these activities are conducted by mining operation department: environmental project (sediment pond, settling pond), tailing storage facility (TSF) and also mining geotechnical infrastructure, such as rock drain and counterweight. In addition, mining operation department is also responsible to manage mine dewatering and mine earthwork activity, such as daily operational mine pumps (pit dewatering), pit service, mine earthwork and haul road maintenance (mine access, mine road, haul road, rom pad and processing plant area). Correspondingly, mining operation department is also responsible to manage ROM pad area and to coordinate with grade control geologist to do ore handling to crusher at processing plant area. At this point, it is clear that daily operational of run-of-mine area (ROM pad), ore loading and hauling in order to transport ore to crusher (at processing plant area) is conducted by mining operation department through coordination with grade control geologist (mine geo services department).

Next, mining operation department is responsible to conduct and to manage mining operation engineering. At this point, these areas of responsibility are:

- Execution of mine plan, communication and coordination. First of all, mining operation is conduct pre start meeting (tool box) as per early shift requirement. This pre start meeting is conducted with mining operation superintendent and shift supervisors/foreman). Safety issues and health issues from previous shift. Actual production (ore mined, waste removal, mine production performance). Review of difficulty and constrain from previous shift. Communication of mine plan for next shift (superintendent and mining supervisors). Next, pre-start meeting with mine operators on daily basis is conducted every start of the shift. Furthermore, on weekly basis, safety talk and health talk (tool box meeting) is conducted by mining operation department, collaboration with HSET department (safety officer, on-site doctor, environmental engineer, mine trainer and if required presenter from another department, such as from mobile maintenance plant department in order to present about tyre awareness).
- Planning: planning of mining fleet (excavator and hauler based on mine planning), mining fleet allocation for multiple pit operation, planning of mine operator's allocation (manpower

management). Also, to conduct communication and coordination with other department (technical support), such as mine planning engineer, mine surveyor, geotechnical engineer, grade control geologist in order to conduct mining activity. Next, to review mine plan based on mining operation engineering point of view, for example review mine plan (based on mine planning engineer's schedule) versus actual (actual production data for ore and waste). Next, to review of operational constrain from mining operation. Also, to review of fleet management system and mining manpower (mining operator) based on mining operation engineering point of view.

- Report to mining operation management about safety issues, health issues, general operational issues. Actual production data for ore and waste, review of previous shift performance (operational constrain for mining operation). Fleet management system (with operational constrain). Fuel ratio (fuel consumption for mining operation activity).
- In addition, these mine blasting activities are conducted and managed by drilling and blasting section of mining operation department. Moreover, it can be seen that these activities are also managed by drill and blast section of mining operation department:
  - Drilling and blasting engineering practice: blast planning, drill design of blasthole, explosive engineering, explosive charging sheet and blast design, initiation of explosives.
  - Drilling operation for blastholes drilling: drilling area preparation, demarcation or securing drilling area, drilling blastholes and quality control (QA/QC) of blastholes.
  - Blasting operation (daily mine blasting): securing blasting location (area demarcation), charging and firing (blasting): priming explosives, charging explosives, stemming blastholes, explosive tie-up (tie-in), final check, blast clearance, firing and post blasting check, blast controlling: blast controlling (blast coordinator) in order to conduct mine blasting in safely manner. The expected result is optimum blasting with no misfire, no excessive fly rock, no property damage, no accident due to excessive toxic fume. In addition, controlled blasting, noise and vibration, misfires and accident prevention.
  - Explosive management and explosive storage: commercial explosive permit (from mines department of Republic Indonesia/KESDM RI and from Indonesia national police/POLRI), management of explosive magazine (on-site explosive storage) and explosive forecasting, explosive order and explosive delivery (coordination with explosive transport and handling of explosives).

Furthermore, it is noted that mining continuous improvement program is also conducted by mining operation department, such as mine blasting with air deck method. Blasting with air deck method can be applied in order to reduce bulk explosive usage and to maintain rock fragmentation by blasting.

Mining Operation in surface mineral mining PT Indo Muro Kencana (PT IMK)

Initially, PT Indo Muro Kencana (PT IMK) is a surface mineral mining (gold and silver mine) that is located in Mt. Muro area, Murung Raya region, Central Kalimantan province, Indonesia. The mining operations of multiple open pits using combination of excavator and haul truck (articulated dump truck) is operated. Particularly, two shifts in a day is performed in order to mine ore and waste. Next, the articulated dump truck with capacity of 40 t and 60 t deliver ore to the mineral processing plant and discard waste material to the waste dump area. Haul truck (hauler) is as the transportation for ore to the crushing plant and waste material to the waste dump. At this point, there are several excavators with various capacities used to achieve the production target. There also dump trucks with the capacity of 40 t to 60 t used for the transportation of the ore to the crushing plant and overburden material to the waste dump.

The list of mining equipment in PT IMK is shown in Table 1.

TABLE 1
Mining equipment.

Unit	Type	Average capacities (payload)
Excavator	Excavator Volvo 750BL	4.5 bcm
Excavator	Excavator Caterpillar Cat 349	3.6 bcm
Excavator	Excavator Volvo 480D	3.5 bcm
Excavator	Excavator PC 400	2.6 bcm
ADT Hauler	ADT Volvo A40G/F	40 t
ADT Hauler	ADT Volvo A60H	60 t

In simple terms, a diagrammatic in Figure 1 is illustrating the typical transportation system in the mine area to the crushing plant (ore) and waste dump (waste). At this time, ADT is the acronym for articulated dump truck (Volvo A40G/F, with capacity of 40 t and A60H, with capacity of 60 t). Additionally, waste dump is acronym to describe area to dump waste material or barren rock. On the other hand, rom pad stockpile is acronym to define ore stockpile at processing plant area. It is located at crusher area (mineral processing plant). There is nothing special in the transportation system except a requirement that the ore production must be met to the target of the crushed rock for the next step of mineral processing.

Next, in term of manpower, mining operation department is consisting of staff level employee and non-staff level employee. Primary, staff level is consisting of:

- Mining management (mining operation manager).
- Mining operation superintendent and D&B (drilling and blasting) superintendent.
- Supervisor level (mine operation supervisor, D&B supervisor, dewatering and earthwork supervisor).
- Foreman (mine foreman, dewatering foreman, blasting foreman).
- Mining engineer (mining operation engineer and drill and blast engineer).

Instead, non-staff level is containing of:

- Mining operators (production excavator, hauler or ADT).
- Mining operators for support unit (support excavator, grader, bulldozer, compactor, flat bed or lowboy, man haul, water truck, mine loader).
- Crew of mining operation engineering (Crew mine engineer/dispatcher, fleet management system, general helper). Mining crews (mine spotter, drill and blast helper/blasting crew, ROM pad helper/spotter, washing pad). Pump operator and dewatering crew. Mining administration (administration coverage for mining operation/production, drill and blast, mine dewatering and earthwork).

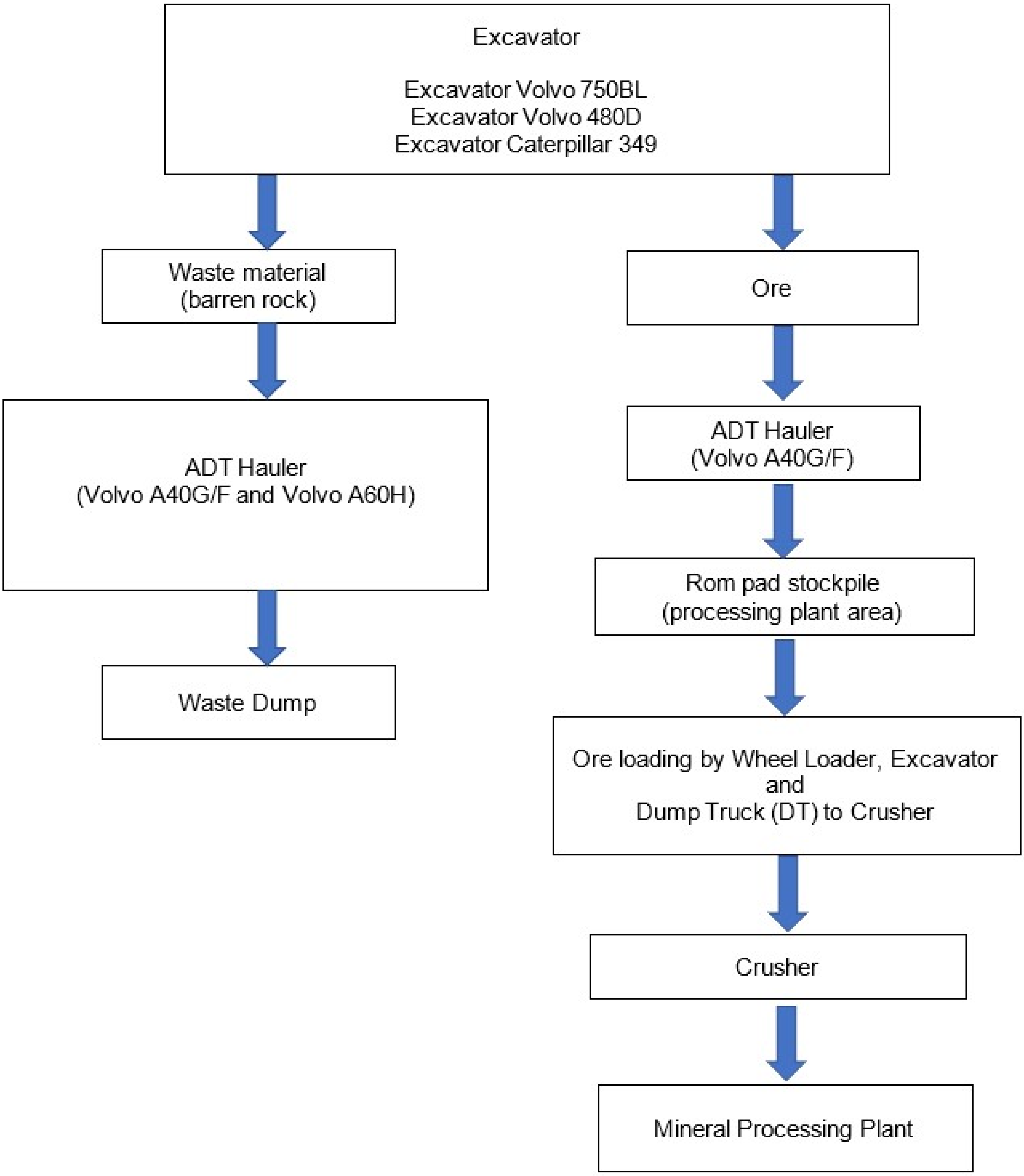


FIG 1 – Mining processes and system in PT Indo Muro Kencana.

MINING ENGINEER IN SURFACE MINERAL MINING OPERATION

Briefly, mining engineer is actively involved and participated in a surface mineral mining operation, especially in daily practice of surface mining operation. At this point, there are two mining engineer's roles in surface mining operation that will be elucidated on this paper, namely mining operation engineer and drill and blast engineer. Typically, the formal education or background for these mining engineers is bachelor degree in mining engineering with suitable mining experience (at least three years of mining operational experience). Correspondingly, it is expected that these mining experiences is also added with:

- Technical skills or hard skills of mining operation experience and mine blasting, such as exposure to digitalisation in mining, fleet management system, exposure to mine blasting, explosives engineering, digitalisation in blasting and blasting economics.
- Mining continuous improvement program. It can be said that mining continuous improvement program as a learning, creativity and innovation processes. At this point, it seems that mining continuous improvement program is an effective option to do collaboration, communication and to show creativity and innovation in order to conduct cost saving (find ways to save the organisation time and money).
- Commercial and mining economics. Exposure to mining budget, cost and risk factors. As a result, mining management need to provide commercial skills and business acumen training to mining engineers in order to recognise how their work make parallel with the KPI of mining operation department and also aligns with financial goals of mining company (organisation's financial goals).

Next, mine operation engineering and drill and blast engineering are two of sub sections of mining operation department. These sub sections are responsible to evaluate, to review of mine planning (mine schedule) and to communicate to mining superintendent and mining supervisor in order to be executed (to be delivered into actual mine production). Moreover, it is expected that mining operation engineer and drill and blast engineer are to be actively contributed in business processes of surface mineral mining operation. In addition, the scope of work for these engineers are from mining operation engineering and drill and blast engineering to actual mining operation (field execution), especially in term of ore mined, waste mined, material handling, loading, hauling, mine blasting (ore waste blasting) and pit development. Initially, mine operation engineering is one sub section of mining operation department. This sub section is in charge to assess mine planning schedule and to determine execution plan with (mining superintendent and mining supervisor) in order to be delivered to actual mining operation, especially in term of ore mined, waste mined and pit development. It is important to note that these mine production plans are implemented as per scheduled by mine planning engineer. Next, drill and blast section that is responsible to manage mine blasting activity to provide blast material in order to support mine production. In addition, this section is also responsible to handle about blast planning and proposal, drill and blast engineering, blasting operation (drilling area preparation and blasthole drilling), explosive charging, blasthole stemming and then to conduct mine blasting in safely manner. This section is also responsible to manage explosive management, to manage explosive permit, management of on-site explosive storage or magazine, explosive delivery and explosive reporting.

The role of mining operation engineer in surface mineral mining operation

First, the role of mining operation engineer in surface mineral mining operation is to be discussed. For the purpose of this paper, the term of mining operation engineer can be defined as a mining engineer in mining operation department that is responsible to manage mining operation engineering, to conduct daily practice of mine operation engineering and also to facilitate coordination between mine planning with mining operation (superintendent and supervisor). In addition, the scope of work for this engineer is from short-term mine plan to actual mining operation (execution), especially in term of ore mined, waste mined and pit development. Normally, the formal education of this engineer is bachelor degree in mining engineering. However, it must be accompanied with sufficient technical skills (mining engineering) and appropriate mining operation experience. Moreover, it is expected that a mining operation engineer is to be actively contributed in business processes of surface mineral mining operation. Furthermore, these are the typical role and responsibility of mining operation engineer in PT Indo Muro Kencana:

- Mining operation engineer is a technical support for mine operation team (to support mining superintendent and mining supervisor) in order to receive correct information about mine plan and to review the execution plan of mining operation. In addition, it seems that mining operation engineer is a facilitator and technical adviser in coordination between mine plan engineer and mining operation (mining operation superintendent and supervisor). It is noted that previous background of mining operation superintendent and supervisor were generally from mining operator's background and then later transformed their career into mining superintendent and mining supervisor. Consequently, it is possible that there will be a potentially lack of engineering judgment for mining superintendent and mining supervisor in term of technical aspect of mining engineering. As a result, engineering judgement from mining superintendent and mining supervisor is ideally supported by mining operation engineer in term of data assessment, analysis and point of view (engineering judgment).

- Mining operation engineer is an engineer to apply mining engineering aspects, safety mining operation and good mining practice in order to deliver mine plan to actual mine operation. In addition, this engineer is responsible to manage mine operation engineering daily practices, such as production control, fleet management system and to organise mining manpower (management/allocation of mining operator), responsible to arrange mine operator for loading, hauling and support (manpower management for pit service, mine dewatering, mine earthwork/road maintenance) and responsible to do mine operation reporting (daily, weekly and monthly report).

Additionally, these are common daily practices of mining operation engineering in PT Indo Muro Kencana:

- Planning:
  - Review of mine plan based on mine planning engineer's schedule and planning of mining fleet (excavator and hauler) based on mine planning.
  - Mining fleet allocation (for multiple pit operation) and planning of operator's allocation (Mining manpower).
  - Communication and coordination with other department, other section and technical support (eg survey team, geotechnical engineer, grade control geologist) in order to conduct daily mining activity.
- To do communication and coordination to execute of mine plan (collaboration):
  - Conduct pre start meeting with mining operation superintendent and shift supervisor/foreman in order to review safety issues and health issues from previous shift and then prepare action plant to execute of daily mine plan.
  - Review of difficulty and constrain from previous shift. Actual production achievement (production data for ore mined, waste removal, total ex-pit mine production). Communication of mine plan for next shift to mine superintendent/supervisors. Assist mine supervisor to conduct pre-start meeting with mine operators on daily basis. Also, on weekly basis, safety meeting mining operation department with HSET (safety officer, environmental engineer, trainer and on-site doctor).
- Review based on mining engineering point of view:
  - Review mine plan versus actual (actual production data for ore and waste).
  - Review of operational constrain from mining operation (review of operational issues related to fleet management system and mining manpower/mining operator).
- Report to mining management (daily, weekly and monthly report). It is important to note that these following aspects will be included in monthly report of mining operation engineer to mining operation manager:
  - Safety issues and health issues. Safety: safety accountability program, such as hazard observation (HAZOB), efforts from mining operation department to manage safety and describe of current mining condition/real situation on the mine.
  - Actual production data for ore and waste. Plan versus Actual: monthly plan, life-of-mine (LOM), actual cause, constraint and reason of operational delay, such as extreme weather condition, technical issue, non-technical reason. Review shift performance, operational constrain (mining operation). Mining fleet: production excavators (main diggers for mine production), hauler (articulated dump truck), support excavators.

- Manpower (mining manpower): Actual mining manpower, requirement for outstanding mine personnel as per life-of-mine (LOM) and mining budget. Fleet management system (FMS): Update of current condition of fleet management system for mine tracking in order to support mine production. Dewatering (mine pumps): main pump (WP), pump location, current status of pump, current condition and actual cause (constraint and reason) of operational delay, others dewatering issue related to mining operation.
- Fuel ratio (fuel consumption for mining operation). Fuel consumption (quantity of fuel for mining usage), re-class fuel (COA – Chart of Account) for financial report and mining budget.

Briefly, it can be said that mining operation engineer's role is a vital part for mining operation department. It is because these engineers have appropriate mining technical skills, sufficient mining operation experience, certificate of national competence (mining frontline supervisory) and a formal qualification (mining engineering). Right now, it is important to note that digitalisation in mining, automation in mining industry and the concept of environment, social and governance (ESG) are an upcoming trend in mining industry in Indonesia. Then, it is projected that workforce evolution is required to be recognised and essentially required by current mining engineer in surface mineral mining operation in order to be commercially competitive. As a result, it is clear that future skill development is required to conduct professional development. These future skills can be gained by training, benchmarking program and mining continuous improvement program. These options are essential as professional development for mining operation engineer in order to be to be adapted with upcoming workforce evolution and also to be commercially competitive in their future career.

Drill and blast PRACTICES IN SURFACE MINERAL MINING OPERATION

Initially, mine blasting is conducted in surface mineral mining operation to breakup ore and waste rock in order to provide broken muck to support mining operation. In general, common blasting practice in surface mineral mining in Indonesia is load and shoot or conventional blasting method with non-electronic (nonel) initiation system. In PT Indo Muro Kencana, mine blasting is conducted to provide broken material (ore and waste) for mine production requirement. Also, it is done to construct pit geometry as per design from mine planning.

Conventional blasting in surface mineral mining operation

Originally, the term of conventional blasting can be defined as blasting with non-sleep blast application. Furthermore, common blasting practice in surface mineral mine in Indonesia is conventional blasting (load and shoot) with nonel initiation system. It is blasted on daily basis (with average of 25 to 30 blasting per month). The blasting practice (such as priming, charging or loading explosives, stemming and firing) is conducted directly in the same day. Usually, daily mine blasting is conducted on lunch time (12:00 noon – 01:00 pm). Nevertheless, in order to provide more tonnage of broken material, mine blasting is occasionally conducted in the late afternoon (03:00–04:30 pm).

Ore waste blasting in surface mineral mining operation PT Indo Muro Kencana

Primary, ore waste blasting can be applied to surface mineral mine with narrow vein condition, where the ore and waste blasting are blasted in the same blasting process. At this point, it is possible that ore waste blasting is carried out by using two methods, specifically: conventional blasting method (with nonel initiation system) and sleep blasting method (with nonel initiation system). Next, ore waste blasting method is applied in surface mining operation of PT Indo Muro Kencana in order to support mining operation. Previously, the blasting practice for conventional blasting, such as loading explosives, stemming and firing, is conducted directly in the same day. However, conventional blasting practice has drawbacks and potential risks associated with blasting activity. At this stage, it is found that the sky will be in dark condition due the sun already sunset on 5:00 pm in northern part of Central Kalimantan province (Mount Muro gold mine area, Murung Raya region, Central Kalimantan). So, it is found that potential risk associated with the afternoon blasting (mine blasting that is conducted on 03:00–04:30 pm) is blaster's ability or failure to identify misfire hole after blasting during post blasting check. It is because due to weather conditions (dark condition on 5:00 pm). At this point, it is possible that conventional blasting practice and afternoon blasting have potential drawbacks and potential risks associated with mine blasting, such as misfire and property damage due excessive fly rock. With regards of these above conditions, it seems that potential risks associated with mine blasting in surface mineral mining (conventional blasting/load and shoot) are misfire and property damage as result of excessive fly rock. Misfire is a potential risk associated with mine blasting activity. It is because of human error due to panic feeling of the blaster when preparing for blasting (tie-up and final check). This misfire condition will create safety issue to mine operation and will potentially delay for mining operation. Next, excessive fly rock due to blasting. Potential risk associated with mine blasting activity is property damage to mine equipment due to excessive fly rock. This excessive fly rock can be caused by secondary blasting, boulder blasting and shallow blastholes with unconfined stemming condition. As a result, it recommended that planned sleep blast combined with the concept of scaled depth of burial is required to apply in order to guarantee a safe work environment in surface mining operation.

The role of drill and blast engineer in surface mineral mining operation

Following, the next focus that will be discussed in this paper is the role of drill and blast engineer in surface mineral mining operation. The section of mining operation department that is responsible to do mine blasting activity is called the drill and blast section. It is responsible to conduct blast planning, to conduct blast operation, to evaluate and to report of drilling and blasting activities to mining operation management. This section is consisting of drill and blast superintendent, drill and blast engineer, drill and blast supervisor, foreman and blast crew. In addition, blasting daily practice and the role of drill and blast engineer in surface mineral in mining operation also will be elucidated. Next, for the purpose of this paper, the term of drill and blast engineer can be defined as a mining engineer that is responsible to conduct drill and blast engineering (explosive engineering), blast planning, explosive management and blast reporting. Currently, the role of D&B engineer is important to manage drill and blast aspects, to implement safety blasting, to deliver blasting plan as per mine plan design in order to support mine production.

It is noted that D&B engineer is responsible to:

- Review of mine planning schedule in order to take it into blasting schedule. Also, it responsible to communicate with mine operation and other related department (technical service, geotechnical engineer, grade control geologist, surveyor, mine planning engineer) in order to conduct mine blasting with safely manner and optimum blasting condition.
- To conduct field inspection and to evaluate (to assess) actual rock condition of blast area in order to create appropriate blast design and planning. To create drill and blast proposal, drill design, blast design (tie up design) and explosive charging sheet (as a guide for blaster and charging crew to do explosive charging). At this point, drill and blast engineer is required to manage drill and blast aspects, to implement safety blasting practice, to deliver blasting plan as per mine plan design and to conduct blasting as per blasting practice. Also, it is recommended that the concept of scaled dept burial is applied in order to create explosive charging sheet. To apply the concept of explosive engineering, it is noted that the concept of scaled depth of burial application and sleep blasting practices is applied in order to ensure a safe work environment in blasting activity.
- Drill and blast engineer is responsible to act as a blasting coordinator to conduct mine blasting as per procedure to provide blast material in order to support actual mine production and in order to conduct mine blasting with safely manner (safe and efficient blasting). Also, as a coordinator to conduct sleep blast practice to ensure a safe work environment in blasting activity.

The daily blasting practice in surface mineral mining operation PT Indo Muro Kencana

These following items are daily blasting practices in PT Indo Muro Kencana:

- Drill and blast proposals. Create drilling and blasting proposals based on mine planning. Selection of blasting geometry (design burden, spacing, bench height, stemming height).

Blasting geometry can be adjusted based on rock conditions in the field (actual rock mass condition). One engineering tool that can be used by D&B engineer to make adjustments to basic blast design is by using the blastability Index (BI) approach as an engineering tool to adjust blast geometry.

- Drill design. The information contained in this drilling design is the target elevation of blasthole depth and drilling technical information. In general, drilling design is created by using Surpac software. Next, this drill design will be used by drilling supervisors and drill operators as a reference in drilling blastholes.
- Explosive charging sheet. Explosive charging sheet is a reference sheet for blaster and charging crew to do explosive charging. It is recommended that the concept of scaled depth of burial is used as an engineering tool to design stemming heights above explosive charge. The concept of scaled depth of burial is implemented as an anticipatory step to reduce the potential for over energy in order to reduce excessive fly rock that can cause property damage to mine equipment.
- Tie up design. Blast design (tie up design) using blast design software in order to manage rock fragmentation by blasting and also to predict of blast impacts to the environment. Prediction of estimated ground vibration and air blast due to mine blasting. Explosive forecast. Planning for the use of explosives required for each blast (quantity of bulk explosives, surface detonator, in hole detonator, dynamite/booster, Lead in Line or LIL). Estimated max rock projection and estimated blast clearance radius based on the concept of scaled depth of burial. Drill and blast reporting to mining operation manager.

The concept of scaled depth of burial as a drill and blast daily practice

Presently, the concept of scaled depth of burial and sleep blast are proposed to implement as daily blasting practice to support safety mining operation in PT Indo Muro Kencana. First, it seems that the concept of scaled depth burial (Chiappetta and Treleven, 1997) is used as an engineering tool to design stemming height above explosive charge. In addition, it is recommended to be applied in daily blasting practice to maintain stemming height above explosive charge in order to prevent over energy, to reduce excessive fly rock possibility and to maintain rock fragmentation by blasting and combination of sleep blast and scaled depth of burial will be continuous implemented as blasting practice. However, it is important to note that excess blast energy (uncontrolled energy) sometimes occurs due to poor of the amount of stemming material and the overcharging of explosives (Figure 2). It is possible that the result of over energy is uncontrolled energy (Figure 2) that can lead to violent fly rock, excessive air blast noise and dust. Also, it seems that good craters and oversized material can be produced. Furthermore, it can be seen that oversize will negatively influence excavator productivity and mine production. At this point, it is expected that rock fragmentation by blasting that is blasted with the concept of scaled depth of burial will maintain safety in blasting to support mining operation.

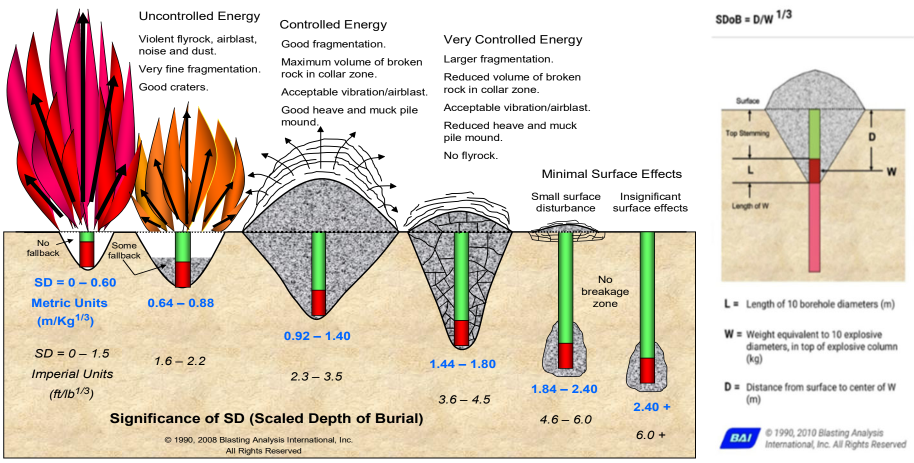


FIG 2 – Scaled depth of burial (Chiappetta and Treleven, 1997).

Currently, the concept of scaled depth of burial and stemming height (m) are used in explosive charging sheet:

- Waste blasting. Waste blasting is stemming $height_{waste}$ = 2.5 m – 3.0 m. Range of $SDoB_{waste}$ = 0.92–1.4 kg/$m^{1/3}$ (controlled energy). The typical value for scaled depth of burial that is used in PT IMK is 1.2–1.3 kg/$m^{1/3}$ for waste blast design.
- Ore blasting. Ore blasting is stemming height $_{ore}$ = 3.2 m – 4.0 m. Range of $SDoB_{ore}$ = 1.44–1.8 kg/$m^{1/3}$ (very controlled energy). The typical value for scaled depth of burial is 1.44–1.5 kg/$m^{1/3}$ for ore blasting.

Furthermore, the concept of scaled depth of burial (Chiappetta and Treleven, 1997) also can be used as an engineering tool to estimate maximum rock projection and estimated blast clearance radius.

The formula for estimated maximum rock projection is:

$$\text{Range Max} = 11 \times SDoB^{-2.167} \times D^{0.667}$$

The formula for estimated blast clearance radius is:

$$\text{BCR or Blast Clearance Radius} = FoS \times 11 \times SDoB^{-2.167} \times D^{0.667}$$

Details are listed in Tables 2 and 3. Table 3 shows the Maximum Rock Projection and the Blast Clearance Radius calculation.

TABLE 2
Scaled depth of burial in PT IMK.

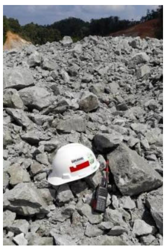
Blast design parameter	Waste blasting	Ore blasting
Hole diameter (mm)	127	127
Stemming rule of thumb	20–24 × hole diameter	25–30 × hole diameter
Stemming (m)	2.54	3.18
Explosive Density (g/cc)	1.15	1.15
Explosive Loading density (kg/m)	14.57	14.57
L (Length of 10 × Borehole diameter) in m	1.27	1.27
D (Distance from surface to centre of W) (m)	3.18	3.82
W (Weight equivalent to 10 × Borehole diameter) (kg)	18.5	18.5
Scaled Depth of Burial (m/$kg^{1/3}$)	1.2	1.44
Scaled Depth of Burial (m/$kg^{1/3}$)	Controlled energy, good fragmentation	Very controlled energy, larger fragmentation
		

TABLE 3
Scaled depth of burial application in PT IMK.

Blast design parameter	Estimated max rock projection (Range Max)	Estimated blast clearance radius (BCR = Blast Clearance Radius)
Hole diameter (mm)	127	127
Formula	Range max = 11 × SDoB $^{-2.167}$ × D $^{0.667}$	Blast clearance radius = FoS × 11 × SDoB $^{-2.167}$ × D $^{0.667}$
Scaled Depth of Burial (m/kg$^{1/3}$)	1.2 Controlled Energy	1.2 Controlled Energy
Range max	11 × SDoB $^{-2.167}$ × D $^{0.667}$ 11 × (1.2) $^{-2.167}$ × (127) $^{0.667}$ = 187.5 m blast radius for mining equipment (m) = 300 m	FoS × 11 × SDoB $^{-2.167}$ × D $^{0.667}$ Blast clearance radius = (2) × 11 × (1.2) $^{-2.167}$ × (127) $^{0.667}$= 375 m blast radius for human (m) = 500 m

Therefore, it can be seen that the concept of scaled depth of burial can be used as an engineering tool to estimate maximum rock projection and estimated blast clearance radius (Table 3). At this point, it can be said that the concept of scaled depth of burial can be used as an engineering tool to predict maximum rock projection of mine blasting and also to design stemming height in order to reduce the possibility of excessive fly rock. Consequently, it will support work safety related to blasting and as a result, mine blasting can be conducted safely and safety of mine operation will be increased.

The concept of sleep blast as daily blasting practice

Initially, there is an awareness from writers in order to campaign about the sleep blast application for blasting practice in surface mineral mining in Indonesia. Correspondingly, risks of mining incident associated with mine blasting is critical for safety in mining operation. Additionally, for the purpose of this paper, the term of sleep blast can be defined as a blast area in which the blastholes have been loaded (has not been tied up) and is not intended to be initiated during the relevant day or shift.

Review of potential risk associated with mine blasting in surface mineral mine

Firstly, some previous cases of mine operational delay related to blasting activity occurred in a surface mineral mine in Central Kalimantan area, Indonesia.

- First case, there was an operational delay to mining operation due to extreme weather condition (extreme rainfall). As a result, the blast location being slept (unplanned sleep blast) for an extended duration. It can be seen that loaded bench and charged explosives remaining loaded in the blasting holes (unplanned sleep blast). This location was blasted on the next day.
- A mining operation delay has been reported. It is noted this operational delay occurred due to breakdown of mining unit that located within radius 300 m from blast location. As a result, the blast location being slept (unplanned sleep blast) for an extended duration. This blast location was blasted on the next day.
- Another case of mining operation delay has been reported and occurred in a surface mineral mine in Central Kalimantan area, Indonesia. It occurred because of misfire event of mine blasting as a result of human error due to panic feeling of the blaster when preparing for blasting. These above conditions are potential cause of operational delay and also potential cause to unplanned sleep blast. As a result, the blast location being slept (unplanned sleep blast) for an extended duration. This location was blasted on the next day.
- Another case of mining operation delay has been reported and occurred in a surface mineral mine in Central Kalimantan area, Indonesia. It occurred because of an excavator was

breakdown within radius less than 300 m from blast location. These above conditions are potential cause of operational delay and also potential cause to unplanned sleep blast. As a result, the blast location being slept (unplanned sleep blast) for an extended duration. This location was blasted on the next day.

Next, it is noted that one of potential risk associated with mine blasting activity in surface mineral mine is misfire. It is possible that misfire in mine blasting is because of human error due to panic feeling of the blaster when preparing for blasting (tie-up and final check). As a result, this misfire condition will create safety issue and it will potentially cause delay to mining operation. At this point, it is recommended that planned sleep blast (sleep load) is required to be applied in order to reduce misfire possibility and also to guarantee a safe work environment in surface mining operation.

The purpose of sleep blast in surface mineral mining operation

Currently, sleep blast is a blasting strategy that can be applied in order to support safety in mining operation. Also, it is note that planned sleep blast application in surface mining operation is an improvement in order to reduce blasting frequency per annum. It is claimed that there are no significant problems in sleep blasting application in surface mining operation. It can be seen that sleep blast is acceptable to maintain safety mining operation. The typical purpose of sleep blast:

- To improve safety and security of blasting activities. Sleep blast will reduce blasting frequency per month and also will reduce the quantity of personnel that is exposed to blasting activity. Also, it is noted that sleep blast will eliminating the panic feeling of the blaster when preparing for blasting. Primarily, sleep blast practice will reduce working load of the blaster. In addition, it is possible that the blaster will be not in a rush or panic to conduct explosive loading (charging explosives and stemming blastholes), to conduct tie up and also to do final check (pre-blast check). Therefore, this condition will make blaster to have suitable time to ensure blast location during pre-blasting to conduct final check. Consequently, mine blasting can be conducted in safely manner by sleep blast application in order misfires possibility.
- To reduce evacuation frequency due to blasting to safe radius (300 m for unit and 500 m for human). Reduction in the frequency of unit's evacuation due to blasting will potentially reduce potential damage to excavator's undercarriage. Similarly, reduction in blasting frequency will reduce the quantity of mining personnel that is exposed to blasting activity. Reduction in blasting frequency per annum will potentially reduce number of frequencies of mine personnel interact with risks associated with blasting activity, such as misfire and excessive fly rock due to blasting.
- Eliminating the afternoon blasting. It is noted that sleep blast practice will potentially reduce the frequency of afternoon blasting (blasting at 3:30 pm or late afternoon). Also, potential hazards during blasting clearance can be controlled safely by blaster and blast coordinator when blasting during lunch break (12:00 pm – 1:00 pm). As a result, blasting can be done during lunch break. It can be conducted in safe manner in order to maintain safety mining operation and to reduce the frequency of evacuation of units due to blasting (to safe radius 300 m). As a result, blasting should be done between 12:00 pm to 1:00 pm or during rest time and also annual blasting frequency will be reduced.

Furthermore, potential risks associated with mine blasting in surface mining, especially conventional blasting (load and shoot) are misfire as a result of human error and property damage as result of excessive fly rock. Next, it seems that the concept of scaled depth of burial as an engineering tool is possible to apply in order to prevent accident (property damage) due to excessive fly rock as a result of blasting. Correspondingly, the concept of scaled depth of burial is a strategy that to maintain stemming height in order to prevent over energy, to prevent property damage due to excessive fly rock, to maintain rock fragmentation by blasting, to estimate maximum rock projection and estimated blast clearance radius. The combination of sleep blast and the concept of scaled depth of burial are proposed by the writers in order to improve daily blasting practice and to support safety in mining operation. Next, it is recommended that these two concepts are proposed to be combined and to be implemented as daily blasting practice in mine blasting in surface mineral mine in order to support safety mining operation. Certainly, it is possible that safety and security of blasting activities and also surface mining operation will be improved by sleep blasting application with combination of the concept scaled depth of burial.

WORKFORCE EVOLUTION AND FUTURE SKILLS FOR MINING OPERATION ENGINEER AND Drill and blast ENGINEER

Workforce evolution in surface mineral mining operation

First of all, the term of workforce evolution can be defined as an evolution in workplace in term of usage of latest technology, for example workforce evolution in mining operation in a surface mining company. Generally, this process is occurred parallel with latest technology in mining industry. It seems that workplace evolution can give benefit to mining company in order to prepare for future growth. In general, these are common conditions of workplace evolution in surface mineral mining operation in Indonesia (past, present and future workforce evolution):

- Past workforce evolution:
  - Mining method: surface mining operation (open pit) with conventional truck and shovel mining method, with conventional technology, such as diesel fuel machinery with minimum use of digitalisation in mining operation (radio communication with limited internet application).
  - Mine planning: conventional or manual mine planning, early stage of mine planning software, internet and also conventional method of mine reporting (early stage of mining software or internet technology and still combined with the usage of paper to do mine reporting).
  - Mining operation: early stage of the use of digitalisation in mining operation and and mine technology. Dispatcher with manual visualisation about line up of mining unit (excavator, hauler, bulldozer, grader) and mining operator arrangement (manpower).
- Present workforce evolution:
  - Mining method: surface mining operation (open pit) with conventional truck and shovel mining method.
  - Mine planning: medium advanced application of mine planning software, internet technology and combined with drone technology and also with geographic information system (GIS) application in mining. In order to support mine planning and mine operation activity, at this time, it seems that drone application (aerial or airborne pictures) and geographic information system (GIS) application in mining are used by mining engineer to conduct mine planning and mine operation activity.
  - Mining operation: surface mining operation with combination of the use of digitalisation in mining, software or internet technology and early stage of automation in mining (automation in mining equipment). It seems that hybrid technology of conventional technology (such as diesel fuel machinery) is combined with latest technology of electric vehicle. At this stage, it can be noted that the usage of blast design software for drill and blast engineering (to create blast design or tie up design and also digitalisation in blasting) is become a new trend for young blasting engineer in present workforce evolution in Indonesia. Moreover, it seems that drone application (aerial or airborne pictures) and geographic information system (GIS) application in mine blasting are also become a new trend of current workforce evolution as it is used by blasting engineer to conduct blast planning and blasting operation activity.
  - To reduce the use of paper for reporting:
    - Digitalisation pre start of mining unit (wheel type unit, track type unit, LV).
    - Digitalisation (visualisation) of line up mining unit (excavator, hauler, bulldozer, grader) and mining operator arrangement.

  - Implementation of fleet management system (mine haulage tracking). Dashboard for mining management (dashboard for monitoring module: manpower mining, mining equipment, production reporting).
  - Digitalisation reporting in safety accountability program (SAP), such as HAZOB and Take 5.
  - Awareness and early stage of implementation of the concept environmental, social and governance (ESG) in mining.
- Future workforce evolution:
  - It is expected and predicted that in the future mining operation system will be operated with maximum use of digitalisation in mining and with maximum use of mine automation or tele remote operation. It is predicted that surface fleet management system will be entirely implemented with real-time-location-tracking system and collision alerts, short-term operation planning and activity scheduling.
  - It is predicted that in the future, digitalisation in mine blasting will become a common practice for drill and blast engineer in surface mineral mining operation. In addition, it seems that digitalisation in blasting will be collaborated with combination of blast design software and the use of drone application (aerial or airborne pictures) and geographic information system (GIS) application in mining in order to create better drill design, better blast design (tie up design) and also suitable explosive charging sheet. Next, it is predicted that automation in drilling (blasthole drill rig) and automation in charging explosives (explosive charging) will be developed in the future. Furthermore, it is expected that these future innovation in term of digitalisation in blasting will support mining operation activity in order to increase mining productivity and mine safety.
  - Advanced awareness and progressive implementation of the concept of ESG (environmental, social and governance) in mining operation.

Future skills for mining engineer in surface mineral mining operation

Preliminary, as an awareness for mining engineers in order to adapt with future workforce evolution, it is recommended that these future skills, such as hard skills or technical skills and soft skills (such as leadership skill) are essentially required for mining engineers in order to be commercially competitive in their future career. Moreover, it is expected that in the future, these future mining leaders will become mining operation superintendents, drill and blast superintendents and also mining operation managers.

Future hard skills for mining engineer in surface mineral mining operation

First of all, it can be said that hard skills are technical skills for mining engineer, such as advanced techniques in digitalisation (mining software that is combined with drone application, geographic information system/GIS application and advanced techniques in usage of automation in mining) will become common skills and common practice in the future mining industry. In addition, strategy and action that will support future hard skills for mining engineer in surface mineral mining operation is the mining continuous improvement program.

Previously, it is noted that a group project that includes competencies from various group member is participated in a mining continuous improvement program. This mining improvement program is arranged and conducted by head office of mining group (BBE Group). At this point, participants from gold mining cluster and coal mining cluster are participated as participants. One group is creating and conducting in a project (prototype project) in order to reduce the use of paper for mine reporting (less paper usage for cost efficient or cost saving), to promote the use of digitalisation in mining and to support daily mining operation (fleet management and also manpower management in mining operation). Next, this prototype project of mining continuous improvement program is consisted of the application of fleet management system for mining operation and mine production reporting. This project is combined and supported with software programming (created by IT site team of PT IMK) in order to increase digitalisation in mining operation. At this point, this prototype project of digitalisation in mining is applied in term of mine equipment pre start report, mining operator allocation, mine production control (mining dashboard for mining management) and mine production reporting. Furthermore, this application is useful to do mine haulage tracking, to measure operational delay and also to control daily mine production.

Future soft skills for mining engineer in surface mineral mining operation

Sooner or later, it is predicted that soft skills or conceptual skills are essentially required for mining engineer in Indonesia. Currently, these skills are non-technical skills and act as a supplement for hard skills. However, it is predicted that these skills are future soft skills that will be obligatory required for mining engineers in order to be adapted with future work evolution in mining industry. Soft skills that are discussed on this stage are critical thinking, creative thinking skills, strategic planning, analytical skills and leadership skills.

Firstly, critical thinking skill for mining engineer. It is said that critical thinking is ability to see the big picture in complex situations and it is required for mining engineer in surface mineral mining operation in order to be adapted with future workforce evolution. Next, creative thinking skills. It seems that future mining engineers with ability as creative thinkers can find innovative solutions to complex issues in order to develop a mining improvement program. Then, it is clear that strategic planning and analytical skills (skilled analysts) is also supplement skills for mining engineer's technical skills or hard skills. Furthermore, it can be seen that leadership skill is also an essential skill for mining engineer in order to be develop to superintendent level and then to managerial level in mining industry. Furthermore, in the next level of career in mining industry (managerial level), it is clear that strong leadership skills, interpersonal skill, communication skills and active-listening skills are compulsory required for future mining manager. In addition, problem solving skills and also decisional skills are soft skills that are required to be gain for mining engineer in order to be competent and to be commercially competitive in the future. Moreover, in order to be adapted with the future workforce evolution, it seems that managerial skills with commercial awareness are also required for mining engineer in order to be competent in managerial level. It is expected that top management, middle managers and low-level managers must have ability to think strategically and also must alert about commercial awareness, such as budgeting of mining operation annual budget and mining economics. It is recommended that mining engineers in low-level managerial level and middle managerial level are given extra exposure to mining budget, cost and risk factors that drive organisational performance, to consider revenue and to mitigate risk.

Strategy to advance future skills for mining engineer in order to be adaptive with future workforce evolution

First of all, it can be said that these strategies can be proposed to advance future skills of mining engineer in order to be adaptive with future workforce evolution in mining industry. First strategy is skills development with formal training and competencies for mining engineer in order to advance their technical skills or hard skills. At this point, formal training or professional development program about mining operation and mine blasting, for example exposure to digitalisation in mining, fleet management system, mine blasting (digitalisation in blasting, drill and blast planning, explosives engineering practice and blasting economics).

Secondly, the next strategy to advance future skills of mining engineer is on the job training (secondment program) that is consist of coaching and mentoring from superior level (superintendent or manager level). Also, it is suggested that job delegation or acting role is a strategy to advance future skills for mining engineer, for example opportunity to work and to act as an acting senior mining engineer or superintendent level). Next, benchmarking is another strategy that can be applied to advance future skills for mining engineer in order to be adaptive with future workforce evolution in mining industry. Currently, benchmarking can be defined as the process of measuring products and processes compared to organisations that acknowledged to be leaders in one or more aspects of their operations. It is recommended that benchmarking is conducted to other mining company that has an advanced mining technology. It seems that benchmarking (to another mine site or to another country) provides essential perceptions to give new ideas to mining engineer. Moreover, it is possible that this is an opportunity for young mining engineers to recognise about their current practice of mining operation compares with similar mining operation from other mining companies. Furthermore, benchmarking activity can also benefit mining company to identify areas, mining systems or processes for mining improvements.

Thirdly, the next strategy to advance future skills of mining engineer is professional development program, such as attend technical mining conferences or international mining seminars and also to conduct benchmarking. At present, it can be seen that mining seminars or international mining conferences are occurred in the physical world (offline conference or seminar) and others can be attended by online, such as Zoom and Teams. As an alternative, mining engineers can take advantage of the online videos and many podcasts that explain about mining engineering skill development and other important mining issues. At this stage, mining engineering skills such as digitalisation in mining operation, automation in mining equipment, digitalisation in blasting, and current trend of global mining technology.

Furthermore, these strategies also can be used to develop soft skills or conceptual abilities of mining engineer in order to keep up to date with changes in mining industry, especially changing technology, digitalisation and trend in area of mining operation (surface mineral mining). It is recommended that one strategy to develop conceptual skills for mining engineers is to consistently read mining engineering journals (such as AusIMM bulletin, ISEE journal etc) and other sources of information about changes in mining industry. It is suggested that this activity will help mining engineers to be informed and up to date with new information of mining technology and also new ideas in mining operation.

Next, another strategy to advance future skills for drill and blast engineer and mining operation engineer is to participate in a group of mining continuous improvement program. At this stage, it seems that mining continuous improvement program is a learning process, creativity and innovation process for mining engineers. At this point, it can be seen that mining continuous improvement program is an effective option to do collaboration, communication, teamwork, to show creativity and innovation in order to conduct a prototype group project and cost saving program in order to find alternative methods to save the organisation time and money.

Finally, the next strategy to advance future skills for mining engineer (drill and blast engineer and mining operation engineer) in order to be adapted with future workforce evolution is exposure to commercial aspect, mining budget and mining economics. At this stage, it is suggested that mining engineer is given exposure to mining budget, mining cost and also exposure to risk factors that can drive performance of mining company. As a result, mining management (top management) need to provide commercial skills and business training to mining engineers in order to identify how their work performance and to make matching with the key performance indicator (KPI) of mining operation department (aligned with financial goals of mining company or organisation's financial goals).

CONCLUSIONS

The main purpose of this paper is to elucidate about workforce evolution and future skills in surface mineral mining operation. It is predicted that in the future, workforce evolution in mining operation will be advanced digitalisation in mining in order to increase mine safety and mine productivity. It is predicted that future workforce evolution in Indonesia is mainly focus on implementation of digitalisation in mining operation and advance technology of mining operation system, such as mining operation system with automation and digitalisation for remote operation.

Also, it is predicted that digitalisation in mine blasting is combination of blast design software with the use of drone application (aerial or airborne pictures) and geographic information system (GIS) application in mining in order to create drill design, blast design (tie up design) and explosive charging sheet. Also, in the future, it is expected that automation in drilling (digitalisation of blasthole drill rig) and automation in charging explosives (explosive charging) will be applied in mine blasting activity to support mine operation. Also, in the future, it is expected that digitalisation will be fully applied in mine production reporting (such as dashboard for mining management). It seems that this digitalisation in mining program will be useful to reduce the use of paper (cost saving program). In addition, digitalisation in mining will be useful in term of safety and environment aspects. Furthermore, it is predicted that advanced awareness and progressive implementation of the concept environmental, social and governance (ESG) in mining will become a new trend in the future of mining operation in Indonesia. Next, it is expected that workforce evolution in mining industry in Indonesia will give attention on exposure to mining economic. Next, it is expected that in the future, the role of mining engineer (mining operation engineer and drill and blast engineer) is still a vital aspect for mining operation in surface mineral mining operation in Indonesia. Additionally, mining operation engineer is a mining engineer that is responsible to manage mine operation engineering daily practices, for instance production control, fleet management system and to organise manpower of mining operation (mining operator), to manage mine dispatch activity and also to do reporting for mine operation management (mining operation superintendent and mining operation manager). Next, the second role that is discussed is the role of drill and blast engineer in surface mining operation. It is clear that this role is also a significant role to surface mining operation daily practice. This engineer is responsible to implement safety blasting practice, to deliver blasting plan as per mine plan design, to conduct blast design practice and explosive engineering practice in order to support mine production. In addition, it is expected that these future innovation in term of digitalisation in blasting that will support mining operation activity, to increase mining productivity and to support mining safety. In addition, future skills for mining engineer can be defined as future skills both technical skills or hard skills and also soft skills that are required for mining operation engineer and drill and blast engineer in order to be commercially competitive in future. Soft skills (such as critical thinking, leadership skill, managerial skill and commercial awareness) as supplement for hard skills, are also required for future skills for mining engineer in order to be adapted with future workforce evolution. In conclusion, it is clear that awareness of workforce evolution and future skills development are essentially required for mining engineer in surface mineral mining operation in order to be adapted and commercially competitive in the future workforce evolution. It is important to note that digitalisation in mining, automation in mining, the concept of ESG and commercial awareness are some upcoming trend in the future mining industry. It is projected that in the future, these young mining engineers will become mining leaders, such as mining superintendent, drill and blast superintendent and also mining operation manager. As a result, it can be seen that future skills development, such as professional development program, benchmarking program and mining continuous improvement program are essential for mining engineers in order to be adapted with future workforce evolution and to be commercially competitive in their future career.

ACKNOWLEDGEMENTS

The authors greatly acknowledge the managements of PT Indo Muro Kencana (PT IMK) who gives permission to utilise the data used in this paper.

The authors also would like to express appreciation to Mr. Sutarno Putro (Director of Operation PT IMK) and Mr Lasher A Silitonga (Head of Department, Mining Operation Department PT IMK).

The authors also would like to express appreciation to Mining Operation department PT IMK (operation section, drill and blast section, mining operation engineer, drill and blast engineer) as a team to conduct mining operation daily practices and to perform blasting practices.

The authors also would like to express appreciation to Dr Awang Suwandhi, Mr Dwihandoyo Marmer and Mr Widiyantoro Pamungkas.

REFERENCES

Chiappetta, R F and Treleven T, 1997. Expansion of the Panama Canal, in *ISEE Blasters' handbook* (ed: J F Stiehr), 18th edition, pp 389–392 (International Society of Explosives Engineers: Cleveland).

Innovations

A day in the life of a mineworker in 2045

J Bassan[1], C T Farrelly[2], G McCullough[3] and P Knights[4]

1. Leader – Integrated Operations and Remotization, Hatch, Melbourne Vic 3000. Email: jarrod.bassan@hatch.com
2. MAusIMM, Partner, Indago Partners, Camberwell Vic 3124. Email: colin.farrelly@indagopartners.com
3. Leader – Digital, Hatch, Brisbane Qld 4000. Email: george.mccullough@hatch.com
4. MAusIMM, Professor, School of Mechanical Engineering, University of Queensland, St Lucia Qld 4072. Email: p.knights@uq.edu.au

ABSTRACT

By 2045, carbon-neutral mines will be economically producing products that are vital for the world's transition to renewable energy. After overcoming significant technical challenges (and the investment of significant capital), leaders have successfully eliminated the use of diesel and other fossil fuels by introducing a wide range of new decarbonisation technologies. These leaders will be reaping the benefits of lower production costs (resulting from elimination of diesel), stable and predictable operations, and easier access to capital for their future projects. This paper describes a future scenario of how a net zero carbon and zero-entry mine could operate by taking maximum advantage of technologies in development or already proven in other industries.

Some miners have been unsuccessful in their efforts to reach decarbonisation targets. Instead, they have been forced to close or offload their assets to be acquired by operators with better sustainability credentials, or, in some cases, to indigenous or community-based enterprises with vested interest in making operations viable and sustainable. Regardless of ownership structure, all successful mining operations will have fostered strong and positive community relations that bring education, health, security and economic development opportunities to the communities while respecting their traditions, land-uses and culture.

As shallow, easy to mine deposits have become scarce, the majority of new mines are underground. Advancements in electric underground technology and the feasibility of 'zero entry mining' (with no personnel in active mining zones) has made it increasingly possible to economically operate underground mines, even at shallow depths. The newest mines have a near zero footprint on the surface, produce no harmful by-products, and are employing in-place or *in situ* methods of extraction that are efficient and low impact. Surface land-uses, such as agriculture and renewable energy generation, continue in the immediate vicinity of the mine, with no significant ground disturbance, community impact or environmental footprint.

Integrated and Remote Operations Centres (IROC) have been in use for almost 30 years, but their role has now changed significantly. Machine learning and optimisation algorithms are reliably running stable and predictable operations that continually adjust operational parameters to maximise value across the value chain. All equipment autonomously executes scheduled missions during normal operating periods and campaign maintenance is practised to provide uninterrupted missions, so the physical remote operations centre has become a 'lights out' centre that is only used to control operations during abnormal situations or emergency response.

In its place, a virtual Decision Optimisation Network (DON) has been established as the nexus for intelligent planning and operational decision-making. The human decision-makers mostly work remotely and are connected virtually with an underpinning information platform that supports both humans and AI tools. The human decision-makers are assisted by advanced AI that significantly improves the quality of decisions that are made by the DON and the timeliness of decisions. The human operators are focused more on mitigating future risks and integrating new technology into the operation.

A small cohort of diverse, energetic professionals manage the mine. They focus their skills and energy on analysing data to find opportunities to continually improve the operation, increase reliability and tune the operating envelopes of the autonomous systems. On-site personnel are still required to service machines, maintain stable operating environments for autonomous machines,

supply consumables and perform other tasks that are not easily automated, but these personnel are never required to directly enter the active mining area.

Enabling the entire automated mining operation is a network of cyber-physical systems that work interoperably. Second and third generation autonomous equipment is much smaller in size and capacity but is operated in larger numbers. The equipment works together in 'swarms' to extract minerals with increased selectivity. A defining feature is that the equipment is designed around electrification, automation, connectivity and remote maintainability. Visibly, the size of equipment is smaller, and operator cabins have been removed, along with other changes to optimise the function of the equipment.

While large amounts of data are captured and stored to enable analysis and continuous improvement, the operation has learnt that only a subset of metrics are necessary to efficiently make operational decisions at the value-chain level. Therefore, an array of AI, including Machine Learning and video analytic techniques, are processing and detecting patterns in the vast streams of incoming data to detect abnormal situations and run equipment efficiently and without deviations. The human supervisor is mainly focused on finding opportunities to further improve the algorithms, or to retrain the AI.

At a strategic level, the whole value chain is dynamically optimised in real time to maximise value and the mission-objectives are automatically cascaded down to the cyber-physical production systems. Most importantly, the optimisation algorithms consider multiple objectives so that humans are primarily responsible for adjusting the weighting of the objectives and setting of assumptions, but not making or executing the short-term decisions.

INTRODUCTION

This paper introduces a hypothetical mining scenario for 2045 and attempts to illustrate how technologies under development today, together with the developing social, political and environmental context in which mining occurs, may influence the operation of mines in a 20-year time horizon. Key features of the future mine are introduced, extrapolating from trends evident today and technologies that are being developed now. The intent of the paper is to inform strategy, roadmaps and forward planning in the mining industry and inspire forward thinking solutions to the challenges that will be faced by the industry.

BACKGROUND

The impact of changes in culture, technology and process maturity can be illustrated by presenting a scenario for the mine of the future. The year is 2045, and Freida (a hypothetical future mine worker) works for a typical international mining company.

Until recently, Freida was based in a remote operations centre in a large city, but she now works from home as part of the DON (Decision Optimisation Network). This long-awaited shift to 'work from home' was finally enabled by a comfortable and high-fidelity spatial-computing headset (Dwyer, 2024). By donning the headset in her home office, Frieda steps into a fully functional virtual operations centre (the virtual operation centre is merely the collaboration and visualisation zone of the DON; it sits upon an infrastructure of information services and AI that supports all decision-making). With the headset on, Freida can position all the screens and dashboards in just the right configuration to meet her needs, while she interacts with the avatars of her co-workers. She is provided with a headset and an allowance to buy an ergonomic chair, but otherwise she does not need expensive workstations and large multi-screen set-ups. Unlike the crude cartoon-style avatars inhabiting the Metaverse in 2020, Freida is unable to distinguish the difference between her real co-workers and the digital representations – it is as if they are right there with her in her home office. To understand the capabilities that may be available to Freida in 2045, we can look at the recent capabilities of the headsets like the Apple Vision Pro (released in 2023) that allow a user wearing the headset to set-up a virtual workspace with multiple applications and collaborate with others using video or avatar-like representations, as shown in Figure 1 (Apple, 2023).

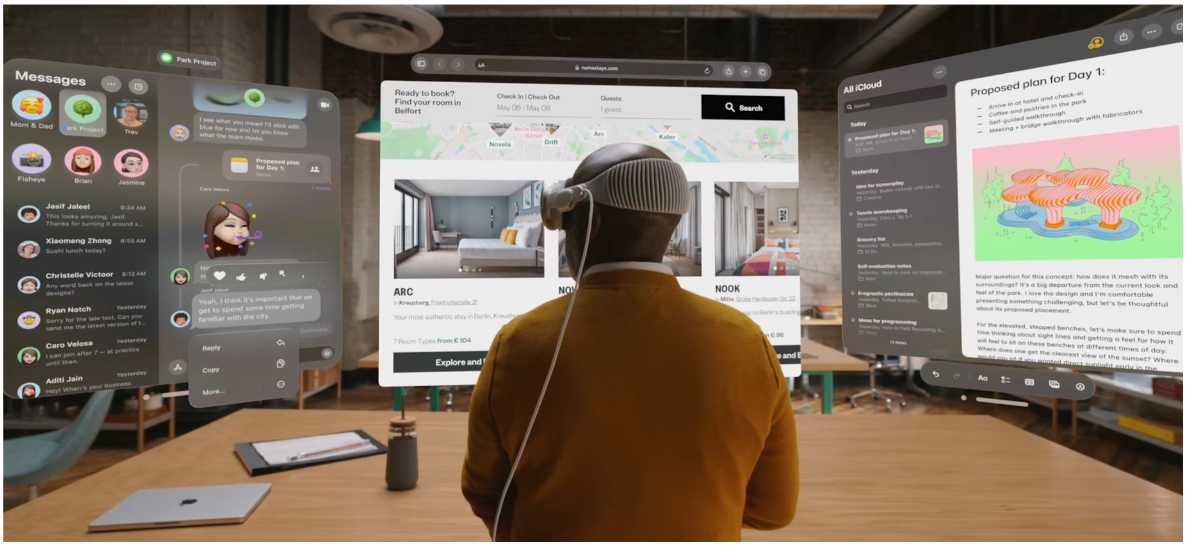


FIG 1 – Spatial computing in 2023 with Apple Vision Pro (image: Apple, 2023).

To set context, Freida was born in 2019 in South America, so she is too young to remember the great pandemic. As a child, she was a big fan of Taylor Swift, although she never learnt to speak English because machine translation services were so advanced that seamless machine translation (powered by AI) across languages has allowed her to communicate effectively with all her friends and colleagues in the USA, Canada, Australia, China and the new federation of free and democratic states spanning central Asia and parts of eastern Europe.

The world has only been partially successful in achieving the hoped-for energy transition. There is still much work to be done to decarbonise, and many regions of the world are subject to increased food and water insecurity resulting from climate change. Consequently, social and political unrest have become more common, and many governments have become reactive to short-term pressures. This creates an incredibly challenging environment for mining companies to operate within – on the one hand, there is high demand for minerals, but they are at constant risk of becoming targets for opportunistic politicians. Successful companies focus on providing a strong net positive impact to the communities and regions they operate within, and view it is a precondition to being able to deliver profit to shareholders.

Freida's role is integrated production supervisor for a large underground mine, and, when on shift, she is responsible for fulfilling the automatically optimised production schedule. Because the mine is fully automated, her role does not involve managing people. Rather, she monitors risks to production, prepares mitigation and contingency plans for production risks, investigates deviations and coordinates a response to deviations on the rare occasions that they occur. She receives considerable assistance from the Artificial Intelligence (AI), including Machine Learning (ML), that is seamlessly built into situational awareness dashboards that provide a complete operational picture.

Coordination usually involves maintenance, energy supply, and the teams that program and maintain the configuration of autonomous equipment.

Orebody evaluation context

The orebody was originally developed as an open cut mine but as the depth increased, profitability became marginal. Eventually, even the efficiency gains of autonomous trucks and the cost-savings of electrified vehicles were insufficient to make the mine economically feasible in the long-term. A solution was needed.

In the 2020s, options were evaluated to economically extend the life of the mine. An innovative technique (for the time) was pioneered to evaluate the orebody – it was a fusion of enterprise optimisation of the mine plan (Whittle, 2010), AI and Cloud computing. Enterprise optimisation allowed a single option to be optimised for the entire value chain (mine to port) (Whittle, 2010); AI allowed the generation of a multiple potential feasible options (and filtering out untenable options that would waste computing resources); and the compute power available on the Cloud allowed millions of scenarios to be simulated, optimised and evaluated in a reasonable time frame. The processes allowed the evaluation and optimisation of a wide range of solutions, taking into account different potential mining methods, capital costs of processing facilities and the processing characteristics of the ore blocks (Amini *et al*, 2021). The final selected solution was to develop an underground mine with small and selective mechanical rock-cutting technology.

Social context

Underground mining was also selected because social and political, intensified by food and water insecurity arising from climate change, had resulted in backlash against large, open pit mines, making permitting difficult and the increased opposition to large scale ground disturbances was causing increased instances of blockades, vandalism and invasions by activists that were disrupting nearby mining operations (Owen *et al*, 2023).

Freida, who graduated with first class honours, chose to join the mining company because of its strong and positive relationships with local communities. She is proud to tell her friends where she works and about how the mine has zero impact on the environment as well as a strong positive impact on the growth and opportunities for the nearby communities.

Operational context

The future mine is 'zero entry' – no people are required in the active working areas. Specialised robots (or automated machines) have repeatedly proven feasible for specific tasks in well controlled environments (Knights and Yeates, 2021). In contrast, practical general purpose humanoid robots have remained elusive despite promising prototypes being demonstrated since the 1990s. Consequently, the future mine has a number of specialised automated machines and infrastructure that reliably supports the small-form factor mining machines. For example, robotic machines and automated infrastructure that can perform tasks like:

- Recover and return the mining machines to the surface for repair and overhaul; or
- Perform high-frequency tasks like replacement of cutterheads (which wear frequently) or automated installation of power and wireless network infrastructure.

Human access is rarely required (in exceptional situations only) and services to support people are minimal. Instead, people use space-suit style life support systems that provide breathable air and protection from high ambient temperature at extreme depth (allowing mining to occur beyond the current limits of 4 km). Normal mining operations are locally suspended when humans enter the working areas of the mine, allowing for temporary life support infrastructure to be deployed.

While few people are directly employed on the mine, it has brought significant employment to the local community. Due to their relatively small size, mining machines (and the supporting robots) are frequently returned to the surface for maintenance and overhaul. Due to the mechanical, electrical, hydraulic and digital complexity, a large number of highly trained specialists are required to support the mine.

- Equipment is smaller and can thus be transported readily using autonomous shuttle services to a nearby maintenance facility established in a larger nearby town with sufficient resources. Maintenance no longer needs to occur 'on-site'.
- Most work is conducted during daylight hours within commuting distance of a town, allowing for regular working shifts (8:00 am to 5:00 pm, for example) and opening employment opportunities to a more diverse workforce and wider pool of talent.
- The maintenance work is outsourced, opening the possibility for a maintenance partner to develop regional hubs that efficiently service multiple mining companies and therefore provide economy of scale for a commodity service.

COLLABORATION WITH PARTNERS

The underground mining option faced one significant challenge – it required extremely small mechanical cutting equipment that could selectively mine the narrow veins in the orebody in hard rock to be economic (Vogt, 2016). No equipment supplier had such equipment at the time, although several were in various stages of development; thus, it was classified as incremental innovation (because it was based upon existing platform, albeit requiring miniaturisation, modernisation and augmentation of capability), and thus suited to being developed by a commercial supplier (equipment manufacturer) who already specialises in that technology (Olivera, 2021).

The mining company had to select a partner to develop the required equipment to a level of commercial readiness and reliability suitable for a mine. Equipment reliability was identified as a particular challenge due to the mine being designed as a 'zero entry' mine with no humans in the active mining areas (Knights and Yeates, 2019):

- Procurement model: As the required technology was not a commodity available 'off the shelf', the mining company used a different commercial construct that allowed the direct negotiation of a partnership. Recognising that several companies had the required technical capability and resources needed, the mining company correctly determined that the most important differentiating factors were the ability to align the objectives of the organisations and ability for the partner to sustain a long-term commitment to the project.
- On the supplier's side, the agreement needed to address vulnerability to cash flow and commitment to a long-term pipeline of work that would justify their investment of resources in the project (Doyla *et al*, 2020).
- Piloting was needed: The supplier was given access to a pilot location, and substantial resources, at one of the company's existing underground mines to conduct extensive trials. This constituted a large investment by the mining company in terms of resources, disruption to mining activities and lost opportunity (in the short-term) at the existing mine.
- Long-term contract with the right incentives: As reliability of the equipment was identified as a major risk, and one best managed by the equipment manufacturer, a long-term service-based contract that provided assurance of revenue to the equipment manufacturer, but also correctly structured to incentivise them achieve the required reliability.

Future suppliers of mining machines will used an iterative development processes to accelerate the testing and development of the equipment. The approach is inspired by Agile software development and the successes of SpaceX's approach to iteratively build, test to failure, and learn. Future suppliers will also make extensive use of digital engineering that enables pre-testing everything in the digital environment, from performance and reliability to constructability.

The use of digital engineering on the Next Generation Air Dominance (NGAD) fighter platform (being developed by the US Air Force) provides a glimpse of how digital engineering may be applied to mining equipment design in the future (Losey, 2023). AI can be expected to play a significant role in optimising and accelerating the design process, resulting in more optimised, efficient, and faster designs, thus accelerating the time frame to achieve technology readiness levels (TRL) 7 or 8. Yüksel *et al* (2023) comprehensively outlines six uses of AI in the engineering design process.

STABLE AND PREDICTABLE OPERATIONS

Eliminating, predicting or controlling variability has been a perpetual challenge in mining, because variability reduces the efficiency of operations and results in sub-optimal value from the resource. To reliably meet production targets, miners have used techniques like excess equipment capacity, buffer stocks (stockpiles) and large, expensive and over-engineered equipment (all of which introduce inefficiency) to mitigate the risks posed by the sources of variability that they cannot effectively control or predict.

By 2045, it will likely become feasible to predict more accurately, and therefore mitigate or control, many sources of variability that inhibit efficiency in operations today. Examples include:

- Reliability induced variation: Very accurate prognostics of machine reliability that make unexpected equipment failures extremely rare occurrences. AI and ML are very well suited to being trained to analyse many streams of data to detect the very early signs of condition degradation that would otherwise be unnoticeable. When integrated with effective maintenance processes, potential failures can be detected and monitored, and preventative measures taken before they result in unplanned impacts to production. Basic condition monitoring is common in mining operations today, but much opportunity exists to harness AI/ML to transform the comparatively basic capabilities available today.

- Geological induced variation: Accurately visualising geology of the orebody, using newly available technologies such as Muon Tomography, which uses muons (from cosmic rays) to measure the density of the rock mass from multiple observation points (in boreholes) and build very accurate 3D models of the geotechnical features of the orebody (Schouten and Ledru, 2018; Schouten, 2018). Figure 2 illustrates early capabilities of muon tomography today. The technology holds great promise both in exploration and for accurately modelling the geotechnical features of active mines. By 2045, using ultra-high-energy muon detectors, the mine plan will anticipate the geology and unexpected variations in grade or geotechnical faults will be less frequently encountered during execution of the plan.
- Human induced variability. With widespread automation of the primary production equipment, capability limitations and negative behaviours attributable to individual human operators will be eliminated as a source of variation. Improved data, reporting, access to simulation capability and real-time visibility of compliance to plans (along with better plans) will increase accountability and reduce instances of humans taking decisions (deliberately or inadvertently) that result in otherwise avoidable deviations.

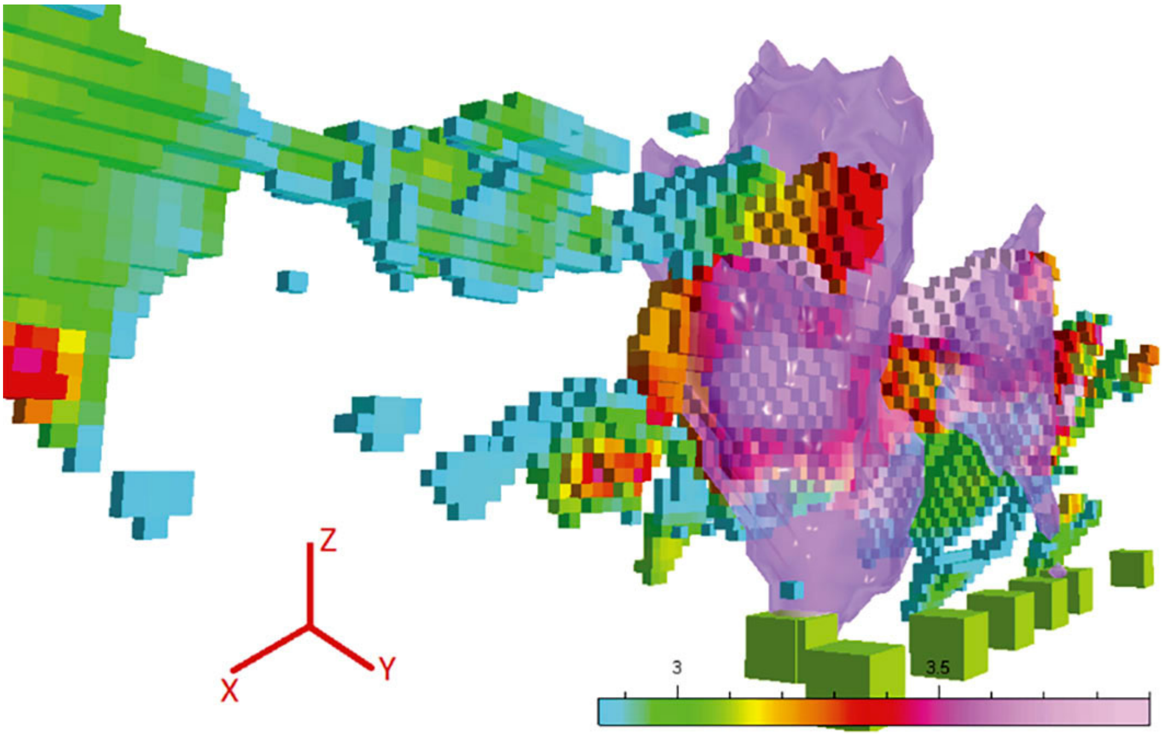


FIG 2 – 3D Block model of density obtained from muon tomography. Green boxes (bottom right) represent the location of the muon detectors. (Source: Schouten, 2018).

Conversely, Freida likely may have new sources of variability to deal with. Possible examples could include:

- Extreme weather events, at increasing frequency caused by climate change.
- Variability in the price of electricity or the available capacity of suppliers, particularly if relying on grids dominated by renewable sources with less stability and continuity of supply.
- More complex socio-political environments that may be exacerbated by food, energy or water insecurity (Lèbre *et al*, 2020; Owen *et al*, 2023), necessitating more transparency and an ability to adequately respond to concerns of communities; and/or

- Rapid innovation cycles that that require significant process change and which may introduce equipment with lower technology readiness levels.

ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

When Freida was growing up, there was much hype about artificial intelligence (AI), including Machine Learning (ML) and Large Language Models (LLM). A young Freida got in trouble (more than once) for using a general-purpose LLM such as ChatGPT to complete her homework. By 2045, the limitations and strength of AI are well understood, and it is now effectively and safely deployed.

The recently published use of sophisticated AI to assist Ukrainian military decision-makers during the conflict that commenced in 2022, provides insight as to how AI may be adopted within the mining industry in the future. Ukraine acquired access to the Palantir AI platform (originally developed for the US government intelligent services), and has also developed its own capable digital platforms (Bergengruen, 2024; Palintir Technologies LLC, 2024). This enables significantly faster and better operational decisions as to how to best allocate resources to achieve outcomes. Which is to say, AI has enabled one side (Ukraine) to get inside the OODA (Observe-Orient-Decide-Act) loop of its much larger adversary. The defining features that have made AI successful in this context are:

- Ease of use: commanders on the battlefield (and under battlefield pressure) are connected, and easily able to enter information such as observed enemy unit coordinates and request their elimination. The commanders are not exposed to any of the technical complexity, nor do they need to know how the system works.
- Rapid analysis: Advanced AI can analyse information very quickly (in seconds, not hours), which may include the position, capability, and ammunition stocks of different units, as well as topography, satellite photos, drone video, and other information. It is then able to suggest to human decision-makers good options very rapidly (within seconds). The critical advantage is speed and capacity – the AI can perform good analysis very quickly and possesses (for all practical purposes) unlimited capacity to perform the same high-quality analysis as frequently as demanded. Because there is a timeliness dimension to operational decisions, 'good and fast' analysis is more valuable than 'slow but perfect'.
- Human in the Loop: Final decisions are still made by humans because there may be extra context or priorities that the AI is not aware of or is not ethically suitable for. However, the AI has taken most of the load of the human by conducting good analysis and filtering out poor options.
- Self-learning: the AI has been able to learn from the results of each strike, and continually improves the options that it presents to humans as well as enabling it to adapt (change its beliefs) as the capabilities or tactics of the adversary evolve.

In summary, the battlefield application of AI demonstrates its ability to significantly uplift the capability of decision-makers to make tactical/operational decisions, faster and with statistically better outcomes.

It is likely that for any field of operations (including mining), AI will significantly impact all levels of decision-making (as shown in Figure 3), including:

- Strategic decisions: where the use of AI enables vastly more options and combinations of options to be generated then would otherwise be feasible to consider (also alluded to above in the section 'Orebody evaluation context').
- Planning and scheduling: where AI may enable the shortening of planning and replanning cycles. It may allow new data to be incorporated into plans in real-time as mining progresses. It may also enable practical applications of more probabilistic approaches to be applied. This results in better plans that are both more optimised and more likely achievable.
- Tactical decisions: where AI can allow remote operators to more effectively respond to unplanned disruptions, including weather events, geotechnical issues with the rock mass and unexpected (although rare) mechanical problems.

- Equipment Operation: continual application of AI/ML in self-driving or autonomous equipment that becomes embedded in the lower levels of control. Due to the learning and adaptability capabilities of AI, it can be expected that over time, AI is able to achieve incremental efficiency and performance gains from equipment based on real-time feedback.

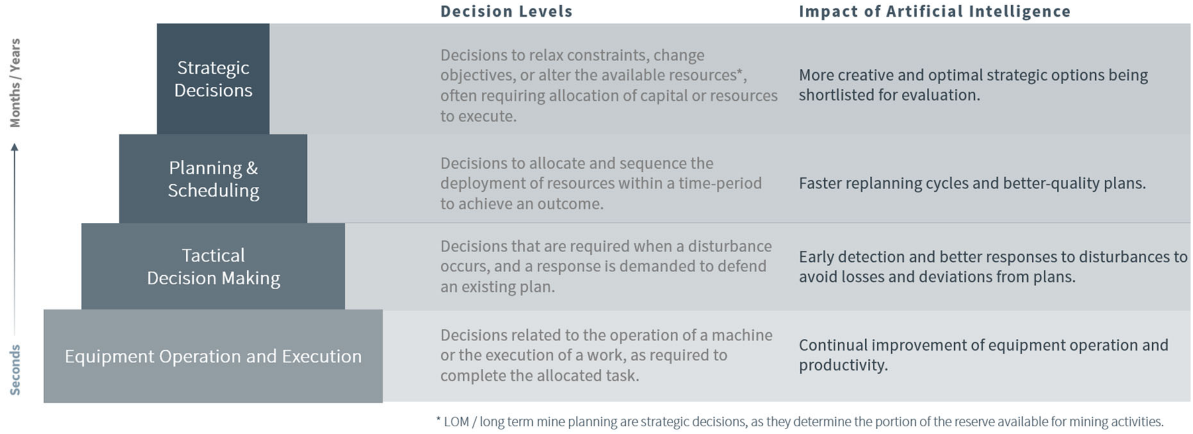


FIG 3 – Opportunities for AI at each level of decision-making.

As these AI platforms become commercially available and accessible, they can be adopted by entities like mining companies who will be able to connect their data sources and, over time, build-up a range of AI powered decision support tools. The expected result is that operators, like Freida, are presented with options, and perhaps even the probable outcomes of the best options determined through probabilistic simulation methods. Operators will consistently make timely decisions with good outcomes, and, over time, the outcomes are on a continual improvement cycle due to the self-learning capabilities of the AI. Just like AI has been able to help one side in a recent conflict to outperform and neutralise the numeric advantage of its adversary, mining companies that intelligently harness AI for decision-making may be able to get inside the OODA loop of the environment they operate within and outperform their competitors.

One final consideration may be the cost or availability of compute capacity required to run all the AI. Advanced AI, as described above, requires immense computing resources that consume enormous quantities of energy. Today, data centres already consume between 1–1.5 per cent of all global electricity usage (IEA, 2023). It is conceivable that eventually the application of AI itself may have to be rationed and prioritised for use on higher-value decisions.

A DAY IN THE LIFE OF OUR MINE WORKER

Frieda starts her 8 hr shift at 8:00 am by donning her spatial computing headset. The bare walls of her home office are suddenly transformed with large screens and dashboards, realistic avatars of her co-workers and even a 3D projection of the orebody that she manipulates with hand gestures. Her shift is conveniently arranged to a ‘follow the sun’ pattern that allows 8 hr shifts during normal daylight hours with operators located around the globe. This has significantly improved the work-life balance for operators like Freida and has contributed to attracting a more diverse talent pool. Female participation makes up, for example, over 50 per cent of the staff of the DON, together with the 8 hr shifts, allows parents of young children to juggle commitments (by contrast, leading countries like Australia and Canada currently achieve approximately 16 per cent participation in mining) (Kansake, Sakyi-Addo and Dumakor-Dupey, 2021). This has gone a long way to reduce the unconscious bias that deterred many talented potential candidates from successfully applying to work in mining.

The mining value chain that Freida monitors and controls is recognisable but has been reconfigured to take advantage of efficiencies possible due to the highly selective and automated extraction method. Some potential implications:

- Because the mining machines are very selective, the mined ore is, on average, of higher grade.
- Mechanical cutting produces a very uniform size distribution and much smaller fragmentation then blasting, requiring less energy in crushing and comminution.

- A larger number of smaller machines (with lower unit cost) would be able to operate simultaneously. This would provide increased redundancy to mitigate lower availability (or design specifications for reliability could be relaxed to keep down costs) and provide flexibility to control grade through blending, where different machines can be turned on/off to achieve the desired optimum blend.
- Pre-conditioning of ore is incorporated into the mining processes to pre-concentrate the ore underground. Already today (in 2024), a number of methods grade engineering technologies exist or are in various stages of development or commercial availability (Dehkhoda *et al*, 2020); By 2045, these technologies can be assumed to be routinely integrated into operations. This has several advantages:
    - Ore feed to the processing plant is much higher grade.
    - Less waste is hauled to the surface.
    - Waste left underground is available of backfilling.
    - Less water is required overall.

The digital systems provide Freida a complete picture of the mine, its current state and its predicted performance over the coming shifts. Freida knows that even a small deviation today can have ripple consequences to the highly optimised schedule.

Freida has access to very advanced digital systems that use a combination of predictive analytics (which uses historical data to predict what will happen next), digital twins (which accurately model how equipment and processes perform) and simulation (which allows a range of future scenarios to be tested) (Farrelly and Davies, 2021). These systems monitor the real time data and predict the probabilities of a range of outcomes. They are enabled with powerful AI that assists in recognising abnormal situations as they start to develop and suggests the best tactical options available to respond.

Freida is presented with a digestible summary of the key risks she needs to monitor and manage to keep production on track. In the 2020s, mines were much more reactive – action was taken in response to an event that had occurred (Bassan *et al*, 2008). By contrast, in 2045, Freida is 95 per cent proactive – she is constantly managing the emerging risks and preventing them occurring (or having good contingencies options in place to protect the plan if the risk event does occur). As a result, the mine runs to plan, process deviations are minimal, and plans can be highly optimised.

Data is available in real time and the quality is excellent, because the autonomous systems rely on the same data to control, and because dedicated data analysts rigorously investigate root causes for any discrepancies in data. Instead of ‘short interval control’, it is now ‘continuous control’. The feedback loop is real time, and when processes deviate outside a narrow bound, the schedule is automatically re-optimised based on the current state and republished to the autonomous equipment.

Long ago, Freida would have had access to an array of CCTV camera footage on screens to provide situational awareness. Now, in her spatial computing headset, she has a real-time 3D model of the mine that she can zoom into any part of the operation, at any angle, and visualise the output of all the connected digital twins that represent the equipment operating in the mine. She can also rewind (to investigate what happened) or even ‘play forward’ to simulate what will likely happen if she takes a particular decision.

First challenge of the day

Freida’s first challenge is not an operational problem. By 2045, under public and political pressure, mining companies have adopted a philosophy of total transparency of all environmental monitoring data, which includes making all data publicly available in real time. This has forced a culture change internally, where any deviations that may impact tailings, water or quality, wildlife or safety of the community are proactively monitored and communicated. Anyone can analyse the same data streams and do their own monitoring if they wish.

Today, Freida has received an alert regarding increased turbidity in the river that flows through the mining lease (although still within acceptable limits). She knows that downstream farmers, who use the stream water for crop irrigation, will be monitoring the same metrics and will soon raise concerns because it affects their livelihood. She investigates and quickly notices that the advanced condition monitoring has already detected a fault with a valve releasing clean treated water. She is presented with three viable options for addressing the issue, and chooses to schedule a valve replacement during the next scheduled maintenance window.

Finally, Freida (assisted by AI) prepares a short notice that will be posted to farmers and other members of the public that subscribe to the mines environmental channel, acknowledging the issue has been detected and the actions that are being taken.

Freida earns her pay

Freida knows the importance of protecting the bottleneck. For this mine, Freida knows that the flotation plant (on the surface) should always be running at full capacity because it is the bottleneck. However, the digital systems are predicting that in the next 12 hrs, the constraint will shift to the mine. The AI has detected the earliest signs of the emerging problem, a warning alert has come up, and Freida is concerned. It will result in deviation from the plan (the first time in three months) and Freida is determined that will not happen. She immediately enlists the help of both the AI assistance and human data analysts to help her track down the cause of this worrying trend, while she starts preparing some contingency plans.

The AI is instantly able to advise her that two (out of the 25) rock-cutting mining machines are starting to exhibit problems, which has resulted in the prediction that the constraint shifting to the mine.

- One machine has developed a vibration signature, which (based on all the historical data that the predictive model has been trained upon) predicts a failure in 8–10 hrs.
- The second machine is about to encounter a higher strength rock formation which will reduce its penetration rate. The geo-technical model is continually updated (based on data collected from the machines as they excavate the orebody) and the unusual rock conditions have just been predicted in the latest update. Because a deep understanding of geophysics and logical reasoning is outside the capability of AI, she consults with a (human) geophysicist using the spatial computing capabilities of her headset. Together, Freida and the geophysicist collaborate (virtually) around an interactive spatial model of the orebody to understand the implications and options.

Together, these two variations (one mechanical, one geotechnical) are outside the bounds of what is anticipated in the plan.

Freida is not deterred – she's got this. She confers with the equipment maintenance team, and they propose an option (from a range of options suggested by AI) to safely defer maintenance on another machine (to keep it in operation) while the machine with the vibration is taken out of service. She can also ramp-up the production rates on the other machines to compensate for the slower penetration (due to the high-strength rock formation), but Freida's concern is the ability to maintain the correct grade into the flotation circuit and the potential for metal loss. She uses the digital twin and associated systems to simulate what will happen if they proceed with this plan. Under the hood, AI generates thousands of permutations on the base scenario which are then simulated to generate a probabilistic range of outcomes. All this happens in seconds, and technical complexity is hidden from Freida (who thankfully only has to interact with one user friendly screen). Freida's concern is unfounded on this occasion – the resultant change in recovery rate in the flotation circuit (resulting from variation in the feed grade) will be minimal, and there is an 80 per cent chance it will remain within bounds of the plan.

Frieda is satisfied that she has an acceptable response plan to deal with an emerging situation, and she can keep the flotation circuit as the constraint without impacting recovery rates. There will be no deviation from the plan on her watch. Meanwhile the production monitoring AI in the digital twin will alert her if the recovery starts to deviate.

FUTURE INNOVATION

Having observed the successful innovations made by equipment suppliers related to new mining technologies (like small mechanical rock cutting machines), the mining company is now aiming to strategically disrupt the industry with a more efficient platform for mining. Unlike the incrementally smaller mining machines, they are now aiming to disrupt the economics of mining.

Rather than aim for a single, 'quantum leap' at great cost and risk to the company, they are instead working on an entire new mining platform, which will be composed of a library of more modular components that can be repeatably configured at low cost and low risk to exploit a range of orebodies. The strategic objectives of this company-wide program are:

1. Accelerate the time to bring a new mine online.
2. Drastically reduce the cost of production.
3. Rapid adoption of best practices through an adaptable, modular architecture for mining that can be used across a range of commodities and orebodies.

Inspiration for this strategy came from the wildly successful platform-based architectures that had disrupted other industries, such as ISO Containers (global shipping); iPhone (mobile phones) and SpaceX (access to space). Motivation to pursue the strategy came from the realisation that a new entrant could disrupt the market. Ansar and Flyvberg (2022) provide an excellent comparison of grand 'quantum leap' projects versus modular, platform-based projects that embody iterative development, modularity, adaptability, and extendibility. Their conclusion is that platform-based projects are faster, better, cheaper and lower risk.

SpaceX is a particular useful case study because its approach and performance can be easily contrasted with NASA. SpaceX started with a grand ambition (initially, to make access to space affordable) but proceeded with a number of smaller rapid incremental developments. Much has been written on the astonishing success of SpaceX, and the iterative and very public testing of their rockets, but a simple comparison of their relative heavy-lift rockets illustrates the point:

- NASA pursued 'grand projects' which are large in scale, very complex and high in risk. The most recent being the Space Launch System (SLS), costing $11.8 Bn to develop and 11 years to first flight (Foust, 2023; US GAO, 2023).
- SpaceX pursued incremental developments and in so doing, developed a modular architecture for space. During the same period as NASA took to develop the SLS, SpaceX developed two heavy-lift systems (Falcon Heavy and Super Heavy). Falcon Heavy's development costs are estimated at between $0.5–0.75 Bn (Ansar and Flyvberg, 2022).

The platform strategy harbours a grand ambition with an architecture of parts and sub-systems that start with smaller, incremental innovations. Each iteration can self-correct, and individual components of the architecture can be substituted or abandoned if they do not show promise. The holistic solution for the grand ambition is managed through a system-of-systems approach to the interconnected parts.

In the case of the hypothetical mining company, it is assumed that one component of their modular platform for minerals is a practical *in situ* extraction method (other components could be imagined to be related to exploration, processing, transport and so-on). For the purposes of an example, electro-kinetic *in situ* leaching (EK-ISL) is selected to represent any one of the many novel extraction methods that have been proposed or lab-tested.

A small-scale experimental trial of EK-ISL of the sulfide ore is underway in an area of the orebody that Freida operates. The EK-ISL method attempts to use a solution that is pumped into the orebody and selectively dissolves the target metal without requiring extraction of the surrounding rock structure. An applied electric field mobilises the dissolved target metal to cathodes, from where the pregnant mineral-rich solution can be pumped up to ground level for processing into metal (Martens *et al*, 2021).

Freida is passionately interested in the trial because it gives her hope that the mine will continue to economically and sustainably meet the world's demand for metals required to complete the low-energy transition and beyond. Her active involvement in the trial provides the research team an opportunity to ground their outcomes to real-world conditions.

CONCLUSIONS

This paper provides a hypothetical potential future scenario to illustrate the interplay between external forces, technology developments and economic factors that are likely to shape mining over a 20-year horizon based upon trends and patterns that are emerging today. The mine, and indeed the mining company, of the future is expected to be characterised by the following features:

1. The social, political, and environmental context of mining will change substantially, and mining companies will need to adapt. This includes providing a positive change to communities and populations who live in the regions of the orebodies. The need is even more acute in mining provinces that are at risk of food or water insecurity in coming decades along with the consequential elevated risk of conflict or social unrest. In such regions, strong positive relations and visible benefits to communities can mitigate the risks.
2. Mining will continue to be a technology intensive industry, and the level of technology dependency will increase as more autonomous equipment, AI, new sensing technologies and other technical developments are integrated into mining operations.
3. Successful mining companies must compete with other industries to attract top talent to be able transition to and operate the technically complex and highly efficient operations of the future. This requires redefining the expectations of the lifestyle of a miner. Living in remote on-site camps or working 12 hr shifts (even with good financial compensation) is an untenable lifestyle choice for many people. Every other industry is undergoing a transition to a low carbon future and competition for talent will be a key challenge for any industry that is considered a technological laggard.
4. The future of mining will be underground for most commodities, and this will require new and more efficient equipment and mining methods that can operate autonomously to extract ore more selectively, with less waste and at greater depth. It is likely that equipment will reduce in size and increase in capability with resulting improvements in both efficiency and reliability.
5. Continued innovation, including research and development of technologies in support of new mining methods will be necessary to adapt to greater scarcity of accessible and economic orebodies, while also meeting the projected increased demands in many minerals.
6. Digital technologies (including AI, advanced analytics and digital twins) will bridge the gap between business planning and the execution of mining activities. Digital systems will become as mission critical as automation and control, and will require a higher level of engineering rigour applied to their design and implementation to ensure their precision, reliability and predictability. At the same time, digital innovation occurs on much shorter time frames (months to years) in comparison to innovation cycles in physical technology (years to decades), which provides the opportunity to continually improve the performance of the mine from its original name plate.
7. The approach to innovation, and even the approach to designing and building mines, needs to change. Mining companies of today are focused on large, bespoke projects, with each mine being uniquely designed and engineered. Eventually, either a new entrant or an ambitious existing player will successfully develop a more modular and adaptable architecture for mining that will enable more flexibility to extract minerals with lower development costs and lower risk profiles.

REFERENCES

Amini, E, Becerra, M, Bachmann, T, Beaton, N and Shapland, G, 2021. Development and Reconciliation of a Mine Operation Value Chain Flowsheet in IES to Enable Grade Engineering and Process Mass Simulations for Scale-up and Strategic Planning Analysis, *Mining, Metallurgy and Exploration*, 38:721–730.

Ansar, A and Flyvbjerg, B, 2022. How to solve big problems: bespoke versus platform strategies, *Oxford Review of Economic Policy*, 38:338–368.

Apple, 2023. Introducing Apple Vision Pro: Apple's first spatial computer, press release 05 June 2023. Available from: <https://www.apple.com/au/newsroom/2023/06/introducing-apple-vision-pro/> [Accessed: 22 Apr 2024].

Bassan, J, Srinivasan, V, Farrelly, C and Knights, P, 2008. A Day in the Life of a Mine Worker in 2025, in *Proceedings of the International Future Mining Conference*, pp 71–87 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Bergengruen, V, 2024. How Tech Giants Turned Ukraine into an AI War Lab [online], *Time*. Available from: <https://time.com/6691662/ai-ukraine-war-palantir/> [Accessed: 22 Apr 2024].

Dehkhoda, S, Salaya, J, Kwak, J and Keeney, L, 2020. Downstream impacts of Grade Engineering® and preconcentration, in *Proceedings of the Preconcentration Digital Conference 2020*, pp 336–344.

Doyla, A, Bliznakov, K, Tonegutti, M, Oudenot, E, Hemmige, H, Kwong, K and Yan, L, 2020. A New Reality for Oil and Gas Procurement Supply Chains, Boston Consulting Group. Available from: <https://www.bcg.com/publications/2020/new-reality-oil-gas-procurement-supply-chain> [Accessed: 21 Apr 2024].

Dwyer, M, 2024. Supercharging integrated operations teams: The co-location advantage, Hatch. Available from: <https://www.hatch.com/About-Us/Publications/Blogs/2024/02/Supercharging-integrated-operations-teams-The-co-location-advantage> [Accessed: 22 Apr 2024].

Farrelly, C and Davies, J, 2021. Interoperability, integration and digital twins for mining, part 2: pathways to the network-centric mine, *IEEE Industrial Electronics Magazine*, 15(3):22–31. https://doi.org/10.1109/MIE.2020.3029388

Foust, J, 2023. GAO report calls for more transparency on SLS costs, *SpaceNews*, September 8 2023. Available from: <https://spacenews.com/gao-report-calls-for-more-transparency-on-sls-costs/> [Accessed: 20 Apr 2024].

International Energy Agency (IEA), 2023. Data Centres and Data Transmission Networks, International Energy Agency, 11 July 2023. Available from: <https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks#overview> [Accessed: 22 Apr 2024].

Kansake, B A, Sakyi-Addo, G B and Dumakor-Dupey, N K, 2021. Creating a gender-inclusive mining industry: Uncovering the challenges of female mining stakeholders, *Resources Policy*, vol 70.

Knights, P and Yeates, G, 2019. The Business Case for Zero-Entry Mining, IEEE-ICIT Automation in Mining Conference.

Knights, P and Yeates, G, 2021. Progress towards zero entry mining, *IEEE Industrial Electronics Magazine*, 15(3):32–38. https://doi.org/10.1109/MIE.2021.3070684

Lèbre, É, Stringer, M, Svobodova, K, Owen, J R, Kemp, D, Côte, C, Arratia-Soal, A and Valenta, R K, 2020. The social and environmental complexities of extracting energy transition metals, *Nat Commun*, 11:4823.

Losey, S, 2023. Future fighter program poses key test for US Air Force's design method, *Defense News*, Aug 30, 2023. Available from: <https://www.defensenews.com/air/2023/08/30/future-fighter-program-poses-key-test-for-us-air-forces-design-method/> [Accessed: 22 Apr 2024].

Martens, E, Prommer, H, Sprocati, R, Sun, J, Dai, X, Crane, R, Jamieson, J, Tong, P O, Rolle, M and Fourie, A, 2021. Toward a more sustainable mining future with electrokinetic in situ leaching, *Sci Adv,* 7:eabf9971.

Olivera, B C, 2021. Innovation in mining: what are the challenges and opportunities along the value chain for Latin American suppliers?, *Mineral Economics*, Springer.

Owen, R J, Kemp, D, Lechner, A M, Harris, J, Zhang, R and Lèbre, E, 2023. Energy transition minerals and their intersection with land-connected peoples, *Nat Sustain*, 6:203–211.

Palintir Technologies LLC, 2024. Palintir and Ministry of Economy of Ukraine Sign Demining Partnership, press release, Palintir Technologies LLC. Available from: <https://investors.palantir.com/news-details/2024/Palantir-and-Ministry-of-Economy-of-Ukraine-Sign-Demining-Partnership/> [Accessed: 22 Apr 2024].

Schouten, D and Ledru, P, 2018. Muon Tomography Applied to a Dense Uranium Deposit at the McArthur River Mine, *Journal of Geophysical Research: Solid Earth,* 123(10):8637–8652.

Schouten, D, 2018. Muon Geotomography: A Novel, Field-Proven 3D Density Imaging Technique for Mineral Exploration and Resource Monitoring, *CSEG Recorder*, September 2018, Canadian Society of Exploration Geophysicists.

United States Government Accountability Office (US GAO), 2023. Space Launch System - Cost Transparency Needed to Monitor Program Affordability, report to Congressional Committees, United States Government Accountability Office, September 2023.

Vogt, D, 2016. A review of rock cutting for underground mining: Past, present and future, *Journal of the Southern African Institute of Mining and Metallurgy*, 116:1011–1026.

Whittle, G, 2010. Enterprise optimisation, in *Proceedings Mine Planning and Equipment Selection (MPES) 2010,* pp 105–120 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Yüksel, N, Börklü, H R, Sezer, H K and Canyurt, O E, 2023. Review of artificial intelligence applications in engineering design perspective, *Engineering Applications of Artificial Intelligence*, vol 118.

Intersection traffic strategy of unmanned truck in open pit coalmines

Q X Cai[1], B Y Luan[2], Y Tian[3], X Lu[4] and W Zhou[5]

1. Professor, School of Mines, China University of Mining and Technology, Xuzhou, Jiangsu Province 221116, China. Email: qxcai@cumt.edu.cn
2. Assistant Professor, School of Mines, China University of Mining and Technology, Xuzhou, Jiangsu Province 221116, China. Email: miningby@163.com
3. PhD, School of Mines, China University of Mining and Technology, Xuzhou, Jiangsu Province 221116, China. Email: border@cumt.edu.cn
4. Assistant Professor, School of Mines, China University of Mining and Technology, Xuzhou, Jiangsu Province 221116, China. Email: xianglu@cumt.edu.cn
5. Deputy director, State Key Laboratory for Fine Exploration and Intelligent Development of Coal Resources, China University of Mining and Technology, Xuzhou, Jiangsu Province 221116, China. Email: zhw19820624@163.com

ABSTRACT

The unmanned driving technology in open pit coalmines is an important technology that relies on innovation to drive the development of the open pit coal mining industry in China's transformation of growth drivers and industrial structure upgrading. It is an important path to solve the shortage of mine truck drivers in the future mining, an important way to improve the working environment of open pit mining personnel, and an important foundation for achieving flexible production capacity in open pit mining to cooperate with the coordinated development of new energy. The communication rules at intersections are key to ensuring the safety and efficiency of unmanned driving in open pit coalmines. This paper proposes a collaborative traffic strategy between unmanned trucks for the single bucket unmanned truck intermittent process system in open pit coalmines. Based on the gap theory, this paper analyses the conflict characteristics and establishes a coordinated traffic strategy for the common intersection and merging conflicts of unmanned truck trucks in open pit coalmines, A multi-agent system simulation platform was built to evaluate the coordinated traffic efficiency under different initial average gap sizes of vehicles, with intersection traffic density, vehicle speed, and gap changes as key indicators. The results show that under the simulation conditions of this article, when the initial average gap of vehicles reaches three (four) times or more of the safe distance, the coordinated traffic performance of intersection conflicts (merging conflicts) is better, and the traffic capacity of intersections is close to the traffic capacity without conflicts.

INTRODUCTION

Unmanned driving technology is an important part of the current intelligent construction of open pit coalmines (Wang *et al*, 2022; Sun *et al*, 2020; Zhang *et al*, 2019). Transportation safety at road intersections is an important area of concern for production safety in open pit coalmines. When there are people driving, the scene generally ensures transportation safety by setting up warning signs and speed limits at intersections. For unmanned trucks, it is important to effectively utilise the characteristics of the unmanned truck vehicle network (Fu *et al*, 2022; Li *et al*, 2017), design reasonable traffic strategies, and coordinate the transportation process of the transport fleet (Čakija *et al*, 2019; Németh *et al*, 2018) to ensure safe transportation at intersections.

Gap theory is a theory proposed in highway driverless driving to coordinate and efficiently pass intersections (Bashiri and Fleming, 2017; Yan, Wu and Dridi, 2014; Pan *et al*, 2022). The theory proposes that by adjusting the local vehicle operating status and rationally utilising vehicle gaps (Ashtiani, Fayazi and Vahidi, 2018; Zheng, 2020), cross traffic between different traffic flows can be achieved instead of the inefficient intersection traffic method of parking and yielding. Jiang *et al* (2022) proposed a vehicle timing optimisation model for automatic intersections based on virtual fleets in order to realise automatic intersection control. Wuthishuwong, Traechtler and Bruns (2015) designed a discrete model of one-way single intersection, used discrete mathematical methods to determine and proposed the safe trajectory of autonomous vehicles for automatic intersection management. Chai (2018) aimed to optimise traffic flow efficiency and proposed an intelligent vehicle parallel gap coordination control method for channelised variable intersections. Mihály *et al* (2021) proposed a model predictive control (MPC) method to control autonomous vehicles to ensure a collision-free passage at intersections. Sun *et al* (2022) proposed an enhanced Dijkstra algorithm for intersections without signal lights, which achieved a lower number of conflicts at the intersection and effectively reduced the total vehicle travel time. Németh and Gáspár (2021) proposed a design method for speed distribution coordination of autonomous driving vehicles in non-signalised intersection scenarios, and solved it through reinforcement learning methods to avoid vehicle collisions and reduce the number of stops at intersections. Fayazi, Vahidi and Luckow (2017) established the vehicle intersection coordination problem as a mixed integer linear programming model, and reduced the number of stops and intersection delays by controlling the vehicle arrival time within the node through planned intersections.

Based on the gap theory, this study aims at the common intersection conflicts and merging conflicts at the intersection of driverless trucks in open pit coalmines. Based on the known right-of-way distribution, the conflict characteristics are analysed, a coordinated traffic strategy is established, and a multi-agent system simulation is built. The platform uses intersection traffic flow density, vehicle speed, and gap changes as key indicators to test coordinated traffic under different initial average gap sizes for vehicles. The research results will lay a theoretical foundation for coordinated traffic at complex intersections under unmanned driving in open pit coalmines.

CHARACTERISTICS OF CONFLICTS AT INTERSECTIONS

The intersection of the open pit coalmine is the part of the road intersection in the open pit transportation system designed by the open pit coalmine to meet the geological conditions, slope stability, mining planning etc, as shown in Figure 1. Therefore, most open pit coalmine intersections have relatively fixed transportation routes, that is, relatively fixed intersection conflict patterns.

(a)

(b)

FIG 1 – The intersection of open pit coalmine: (a) An open pit coalmine dump site; (b) End-slope road of an open pit coalmine.

The methods to resolve intersection conflicts mainly involve two aspects: right-of-way allocation and coordinated traffic. The right of way refers to the priority of traffic in traffic or at an intersection. According to the state of the vehicle, open pit coalmines usually follow the rules of ‘empty vehicles give way to heavy vehicles, turning vehicles give way to straight vehicles, branch line vehicles give way to main line vehicles, and downhill vehicles give way to uphill vehicles. ‘Go first, the party with conditions to give way must let the other party go first, ordinary vehicles must give way to special vehicles performing tasks, and any vehicle must give way to operating road maintenance machinery’ and other principles. For driverless trucks, since there are no human factors issues, some principles can be adjusted. Table 1 shows the recommended right-of-way allocation method in this study.

TABLE 1

Right-of-way at unmanned truck intersections.

No.	Conflict vehicles 1	Conflict vehicles 2	High priority	Explanation
1	Unmanned mining truck	Auxiliary equipment	Auxiliary equipment	Prioritise completion of auxiliary links such as watering, road construction and management of personnel vehicles
2	Unmanned road leveling vehicle	Unmanned road leveling vehicle	The party with the conditions to give way lets the other party go first	Including turning vehicles, straight vehicles etc
3	Unmanned uphill and downhill vehicle	Unmanned road leveling vehicle	Unmanned uphill and downhill vehicle	Braking and acceleration are easily limited on uphill and downhill slopes
4	Unmanned uphill vehicle	Unmanned uphill vehicle	Unmanned uphill vehicle	It is recommended to avoid single lane ramps
5	Unmanned heavy vehicle	Unmanned empty vehicle	Unmanned heavy vehicle	Heavy vehicle braking is easily restricted

In order to stabilise the unmanned transportation process, we draw lessons from the way in which different processes in the integrated process are divided into different operating areas according to process characteristics. At the same time, referring to the mine automation implementation guidance given by the Global Mining Guidance Group (GMG), it is recommended that unmanned The driving area is operated separately from the manned area. Therefore, in addition to auxiliary equipment, the recommendations given in Table 1 do not consider manned equipment such as manned trucks.

Through right-of-way allocation, high-priority vehicles and low-priority vehicles are always determined. The process of low-priority vehicles giving way to high-priority vehicles is the process of coordinated traffic. This study focuses on the coordinated traffic between unmanned transport trucks. According to research, it is recommended to use the method of stopping and giving way to coordinate passage with auxiliary equipment.

The types of conflicts at intersections in open pit coalmines can be mainly divided into intersection conflicts and merge conflicts. Intersections are mostly a combination of these two conflict forms. The multiple intersection conflicts shown in Figure 1a and the multiple intersection conflicts shown in Figure 1b crossover and merging conflict. In addition, because most domestic open pit coalmines have near-horizontal coal seams, the conflict objects on the truck transportation roads in the pit are mostly uphill and downhill transportation trucks and flat road transportation trucks, that is, there are clear vehicle traffic priorities. Therefore, this study first studies the coordinated traffic strategies for the two conflict types respectively, and then establishes a hybrid conflict model of intersection and merging in the simulation part and conducts simulations to test the coordinated traffic strategies.

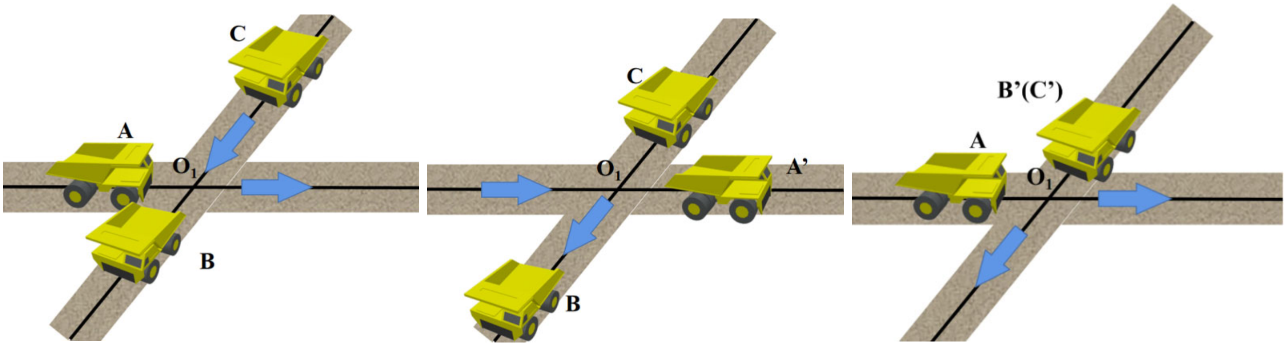
COORDINATED TRAFFIC STRATEGIES AT INTERSECTIONS

The research on intersection conflicts and merging conflicts in this study is based on the premise of known vehicle priority, and the determination of right-of-way allocation is not within the scope of the study.

Cross-conflict coordination strategy

Figure 2 shows a schematic diagram of cross-conflict coordinated traffic, assuming that the BC vehicle transportation direction has high traffic priority. Among them, the earliest passing time of car A is just after car B passes, and the latest passing time is just before car C passes.

Correspondingly, there is also a critical state for conflict. As shown in Figure 2c, the timing of the occurrence of vehicle A and vehicle BC is consistent. The vehicle conflict area can be obtained, and the centre position of the vehicle when the vehicle is in critical state is marked as the four key points AA'BB' of the conflict area, as shown in Figure 3.



(a) (b) (c)

FIG 2 – Cross-conflict coordinated access diagram: (a) The earliest passing time of car A; (b) The latest passing time of car A; (c) Earliest conflict time.

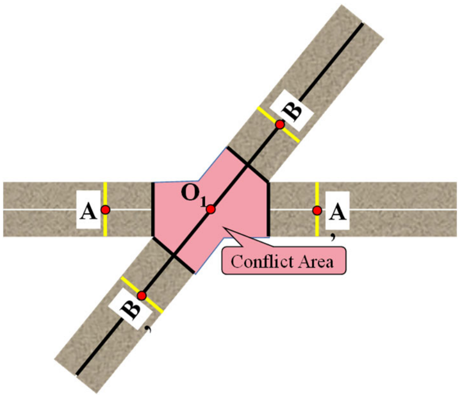


FIG 3 – Areas of cross-conflict.

Therefore, it can be concluded that the condition for no cross-conflict occurring is that only one vehicle can exist in the conflict area at the same time. The critical state is when one vehicle just drives in and the other vehicle just drives out, then:

$$(t_{x_1 enter} > t_{x_2 exit}) \vee (t_{x_2 enter} > t_{x_1 exit}) \tag{1}$$

Among them, $t_{x1enter}$ is the time when vehicle x_1 enters the areas of cross-conflict; $t_{x2enter}$ is the time when vehicle x_2 enters the areas of cross-conflict; t_{x1exit} is the time when vehicle x_1 leaves the areas of cross-conflict; t_{x2exit} is the time when vehicle x_2 leaves the areas of cross-conflict.

Taking Figure 2 as an example, assume that the coordination objects are vehicles AB. When there is a possibility of conflict, there are two coordination options: speeding up and decelerating.

When using accelerated traffic, vehicle A needs to meet the following requirements after adjustment:

$$t_{Benter} > t_{Aexit} \tag{2}$$

The limiting factors at this time are:

- Whether the speed of vehicle A after acceleration meets the road speed limit.

- Whether vehicle A will collide with the vehicle in front after accelerating.

When the above constraints are met, priority is given to accelerating traffic and improving road traffic efficiency. When the acceleration conditions are not met and deceleration is used, the following must be met:

$$t_{Aenter} > t_{Bexit} \tag{3}$$

However, the adjusted operating status may cause a conflict between car A and car C. From the perspective of system execution, in order to avoid conflict with car A, car C needs to make a second adjustment to car A. Therefore, vehicle C needs to be taken into consideration when considering the coordinated passage of vehicle AB, so that vehicle A after deceleration adjustment will not conflict with vehicle BC, that is, the traffic interval after deceleration is the gap between vehicle BC.

When car A passes right behind car B, then:

$$t_{Aenter} = t_{Bexit} \tag{4}$$

When car A passes just in front of car C, then:

$$t_{Aexit} = t_{Benter} + \frac{l_{BC}}{v_C} \tag{5}$$

Among them, l_{BC}/v_c is the time it takes for car B to arrive at the conflict area and then for car C to arrive at the conflict area when car C is moving at a constant speed. Considering that the gap between two BC vehicles may be large, it is recommended to use the safety distance l_{safe} between BC two vehicles instead of the actual distance in the application.

Therefore, when decelerating traffic is adopted, vehicle A needs to meet the following requirements after adjustment:

$$\left(t_{Aexit} < t_{Benter} + \frac{l_{safe}}{v_C}\right) \wedge \left(t_{Aenter} > t_{Bexit}\right) \tag{6}$$

After determining the conflict judgment conditions, analyse the conflict judgment interval. As shown in Figure 4, this study extends the conflict area by 200 m in the reverse direction of the driving route, and uses the area where low-priority vehicles such as car A are located as an adjustment area to monitor the occurrence of conflicts and adjust the operating status of the vehicles; The area where the vehicle is located is regarded as the monitoring area, and the vehicles in the area are the monitored objects.

This distance can basically cover the common ramp of 15 m step height, 8 per cent slope and 187.5 m length, which meets the right-of-way judgement between uphill and downhill vehicles and flat road vehicles. Generally speaking, the adjustment area of uphill and uphill vehicles includes some slopes, but there are also cases such as the width of some steps in Yimin open-pit coal mine is close to 200 m, so that the adjustment area of flat vehicles may not contain slopes, which is regarded as the cross-conflict situation of flat road workshops.

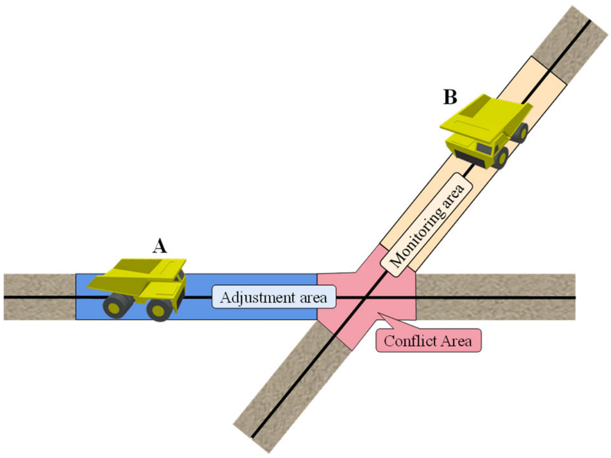


FIG 4 – Cross-conflicting adjustment areas.

Convergence conflict coordination strategy

Figure 5 shows a schematic diagram of the merging conflict. Vehicle A uses the gap between vehicles BC to complete the merge. Vehicle A is a high-priority vehicle and BC is a low-priority vehicle to be adjusted.

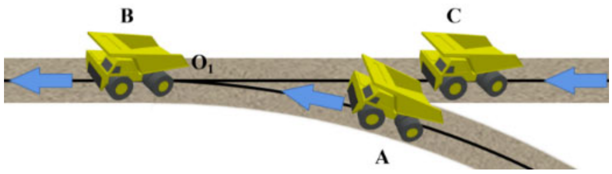


FIG 5 – Merging conflicts diagram.

Merging conflict is the merging of two different traffic flows, so the transportation status after the merger needs to be considered. For example: when car A joins in Figure 5, car AC may need to slow down to ensure a certain safe distance. At the same time, Car A is in the process of turning when merging and needs to slow down to pass. Taking into account the above characteristics of merging conflicts, taking AC vehicles as an example, the specific coordination plan is as follows.

When only coordination outside the conflict area is considered, consistent with cross-conflicts, the condition for no conflict is that only one vehicle can exist in the conflict area at the same time. The critical state is that one vehicle just drives in and the other vehicle just drives out. Equation 1 is also satisfied when no conflict occurs.

When considering vehicle coordination after the merge begins (vehicle A enters the pink conflict area, it is considered to have started the merge, and it completes the merge when exiting), the main idea is to adjust the conflict area, and there may be many ways to adjust. This study studies the coordination of merge conflicts The strategy is formed through continuous simulation-feedback, as shown in Figure 6. Pink is the initial conflict area, and green and yellow are the conflict areas that are increased after adjustment. The details are as follows:

1. BA is the deceleration and turning distance of vehicle A. The purpose of extending BA is to hope that vehicle AB will be in the critical state of Equations 3–11, that is, when vehicle A enters the conflict area and vehicle B just exits, the gap will reach the minimum safe distance. At the same time, we do not want AB to be too long. Since car B is generally faster than car A which is decelerating at this time, BA takes into account the decelerating turning distance of car A. The insufficient vehicle gap will gradually be satisfied or approached as car A drives to point B.
2. O3C is designed with a minimum safety distance. The length of O3C is taken into account that when car A is at point B under critical conditions, the gap between car AC is larger than the minimum safe distance. The redundant O1O3 length can be used in the process of decelerating car A to meet the safe distance of car AB described in (1) above. That is, the

distance between BA+BC reaches or approaches twice the safe distance for accommodating three vehicles ABC.

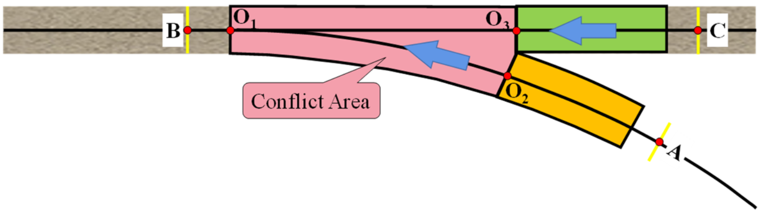


FIG 6 – Merging conflict areas.

Set the adjustment area. It is also recommended that the length of the adjustment zone be 200 m before the conflict point AC occurs.

When there is a conflict between vehicles, there are two coordination solutions: accelerating and decelerating. The judgment condition is: Does car B or C conflict after accelerating? If there is no conflict, the vehicle will pass at an accelerated speed; if a conflict occurs, the vehicle will pass at a reduced speed.

Following model

The purpose of studying the car-following model in this section is to analyse how the vehicle behind it reacts to ensure safe driving when the vehicle at the intersection adjusts its vehicle motion state to avoid conflicts. The car-following model is a theory that uses mathematical modelling to describe the behavioural state relationship between a vehicle and the vehicle in front of it in a single lane where overtaking is prohibited. It analyses the traffic flow characteristics of a single lane from a microscopic perspective. For example, when the vehicle in front decelerates, the vehicle behind it How to make adjustments.

For open pit coalmine truck transportation, safety issues mainly need to be ensured, so this study is based on the Krauss car-following model (Krauß, 1998). The Krauss car-following model is a car-following model based on safe distance constraints. Its basic expression is as follows:

$$L(v_f) + v_f t_r < L(v_l) + g \tag{7}$$

Among them, v_f is the speed of the following vehicle; $L(v_f)$ is the braking distance of the following vehicle; v_l is the speed of the leading vehicle; $L(v_l)$ is the braking distance of the leading vehicle; t_r is the driver's reaction time; g is the gap between the two vehicles.

The meaning expressed by Equation 7 is that when the leading vehicle brakes, the following vehicle brakes immediately. There will be no collision between the vehicles after braking. v_f is the following speed required for the study.

It can be known from the kinematic formula:

$$L(v) = vt_s - \frac{1}{2} b t_s^{\,2} \tag{8}$$

$$t_S = \frac{v}{b} \tag{9}$$

Among them, t_s is the time for the speed to brake to 0; b is the deceleration.

Substituting Equations 8 and 9 into Equation 7, and solving the equation, the maximum safe following speed v_{fsafe} of the following vehicle speed v_f can be obtained as:

$$v_{fsafe} = -b_f t_r + \sqrt{(b_f t_r)^2 + \frac{b_f}{b_l} v_l^{\,2} + 2 b_f g} \tag{10}$$

At the same time, the vehicle itself has a speed upper limit vfmax, a maximum driving speed vflimit restricted by the road, and the expected vehicle speed vf(t)+aΔt set by the controller at the next moment. Therefore, the expected following speed is:

$$v_f = \min[v_{fsafe}, v_{f\lim it}, v_{f\max}, v_f(t) + a\Delta t] \tag{11}$$

Improvements are made based on the unmanned mixing conditions of open pit coalmines. First, the driver's reaction time t_r is adjusted to the vehicle's reaction time caused by factors such as signal transmission and data calculation. Secondly, since the Krauss car-following model takes into account the driving speed of the vehicle in front, the safety distance implied by the car-following model is smaller than the designed safety distance l_{safe}, and the vehicle distance g cannot always be maintained greater than the designed safety distance l_{safe}. Therefore, it is necessary to improve the Krauss car-following model and discuss different situations.

When $g > l_{safe}$, the Krauss car-following model can be used normally for speed judgment; when $g < l_{safe}$, $v_f < v_l$ needs to be maintained to maintain a safe distance. The adjustment model is:

$$v_f = \begin{cases} \min[v_{fsafe}, v_{f\lim it}, v_{f\max}, v_f(t) + a\Delta t] & g > \alpha l_{safe} \\ \min[v_{fsafe}, v_{f\lim it}, v_{f\max}, v_f(t) + a\Delta t, \beta v_l] & g \le \alpha l_{safe} \end{cases} \tag{12}$$

Among them, α is the safe distance coefficient, which is selected according to the vehicle conditions such as vehicle speed controller and reflection time, such as 1.1~1.2. The purpose is to start decelerating when the vehicle approaches the safe distance, leaving space for the deceleration process and improving redundant safety. distance; β is the deceleration coefficient, which is also selected according to the vehicle speed controller, reflection time and other vehicle conditions, such as 0.8~0.9, so that $v_f < v_l$ realises the deceleration process.

Gap distance

The vehicle clearance distance refers to the natural inter-vehicle distance during general vehicle transportation. From the perspective of constraints of the car-following model, if driverless vehicles keep a safe distance from each other, once one vehicle slows down, all the vehicles behind it will slow down. If the vehicle is traveling at a speed of 25 km/hr and suddenly decelerates to 20 km/hr, the speed will be 0.8. According to the deceleration coefficient of the vehicle behind, the speed of the fifth vehicle behind will be directly reduced to 6.55 km/hr, which will have a serious impact on the overall operating efficiency. Therefore, the gap distance between vehicles while driving should be greater than the safe distance. At the same time, the gap distance is also an important factor affecting the coordinated traffic efficiency under the gap theory.

Analysis from the perspective of cross-conflict coordination and communication. For high-priority vehicles, it is necessary to ensure that the gap distance can allow low-priority vehicles to pass. Assuming that high-priority vehicles are 20 km/hr, low-priority vehicles are 25 km/hr, and the road width is 10 m, a distance of at least 16 m is required. This situation can only satisfy vehicles passing through the gap, and a safety redundancy distance needs to be left. At the same time, it is considered that the range of feasible solutions for coordinated passage of low-priority vehicles needs to be increased by expanding the gap distance, especially at multi-vehicle intersections. Therefore, the gap distance can be designed as follows.

$$l_{gap} = n[(d_r + l_{TL})\frac{v_{HT}}{v_{LT}} + l_s] \tag{13}$$

Among them, n is the redundancy coefficient, and the value of n is increased when multiple vehicles cross; l_{gap} is the gap distance, m; v_{HT} is the maximum speed limit of vehicles with high priority, km/h; v_{LT} is the maximum speed of vehicles with low priority Maximum speed limit, km/h; d_r is lane width, m; l_{TL} is truck length, m; l_s is redundant safety distance, m.

Analysis from the perspective of merging conflicts and coordinating traffic. The traffic flow density of the merged road is the sum of the densities of the two tributaries. Therefore, the vehicle gap distance in the tributary should be at least twice the safety distance to ensure that the vehicle gap after the merge is greater than the safety distance, that is:

$$l_{gap} = n \times l_{safe} \tag{14}$$

Among them, n is the redundancy coefficient, $n \geq 2$.

Vehicle adjustment

In terms of vehicle adjustment, it mainly involves vehicle kinematics, dynamics, vehicle control theory, etc. At the same time, depending on the on-site conditions, coordinated traffic may occur during the turn. Therefore, the specific vehicle adjustment plan needs to be designed according to the actual situation of the vehicle. This study provides an adjustment algorithm based on vehicle kinematics under simple linear motion conditions, providing a research basis for complex situations.

Take the deceleration adjustment during cross conflicts shown in Figure 2 as an example. Since vehicle B does not need to adjust, the time when vehicle A arrives at the conflict area is determined. Therefore, in principle, the vehicle's deceleration process is to decelerate as early as possible. The earlier the vehicle decelerates, the smaller the deceleration amplitude of the vehicle will be. After passing through the conflict area, the vehicle's speed will increase in a shorter time. Figure 7 shows the vehicle speed adjustment process. Since the final arrival position does not become a conflict area, the area of the red area and the green area in the figure are equal, then:

$$\frac{1}{2}(t_1 + t_2 - 2t_0)(v_0 - v_1) = v_1(t_3 - t_2) \tag{15}$$

Among them, v_0 is the initial speed; v_1 is the adjusted speed; t_0 is the speed adjustment start time; t_1 is the speed adjustment completion time; t_2 is the time to arrive in the conflict area before adjustment; t_3 is the time to arrive in the conflict area after adjustment.

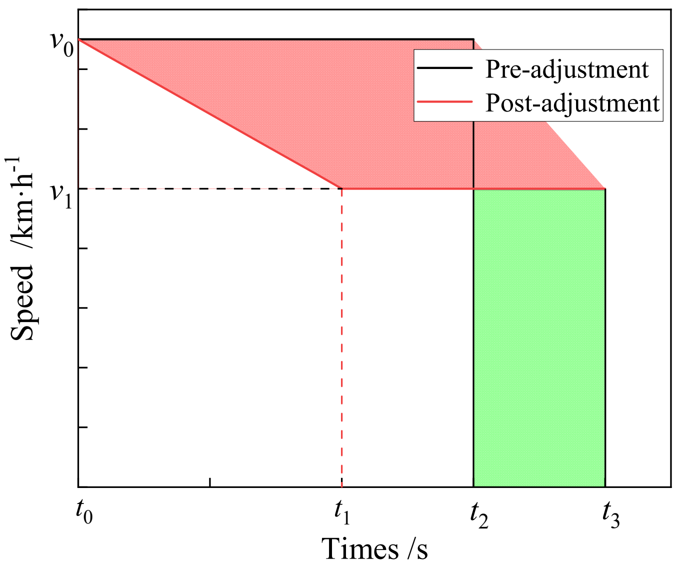


FIG 7 – Speed reduction adjustment process.

The adjusted speed v_1 is the traffic speed $v_{Aaccess}$ of vehicle A, and has:

$$v_{Aaccess} = v_1 = v_0 + b_A(t_1 - t_0) \tag{16}$$

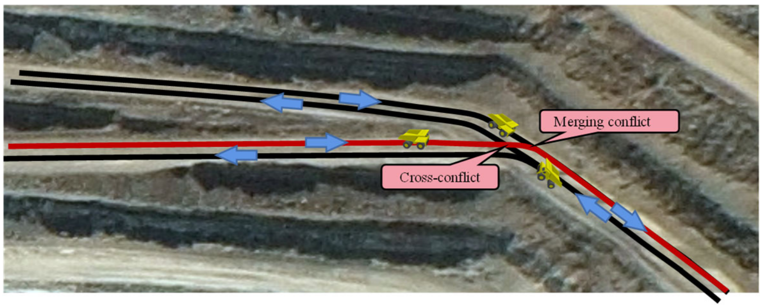
Among them, b_A is the deceleration of car A.

In Equations 15 and 16, the known quantities are t_2, t_3, v_0, and the quantities with known change ranges are b_A and v_1. By iteratively calculating b_A and v_1, a variety of coordinated access methods can be obtained, and the best one can be selected under the set constraints. Optimal solution, possible constraints include car-following model, vehicle control, etc. Generally speaking, choose the faster speed as the solution.

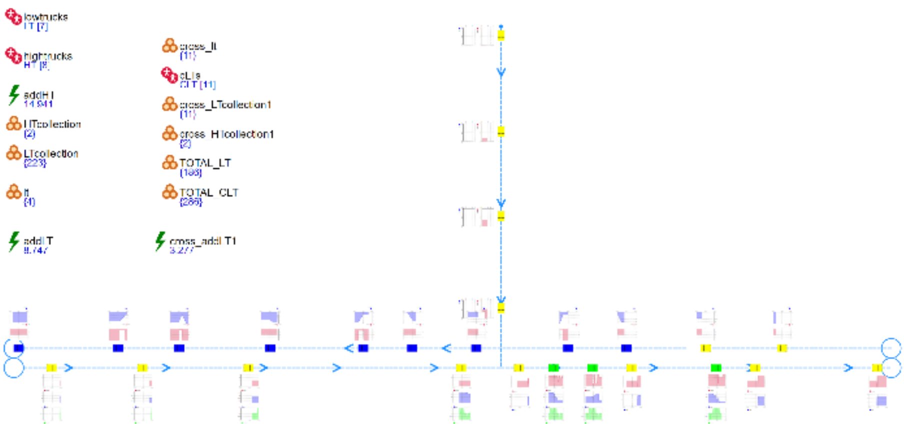
In the simulation part of this study, in order to facilitate testing of the coordinated traffic model, infinite acceleration and deceleration, that is, speed mutation, was adopted. The feasibility of the strategy was judged by analysing the number of speed mutations.

SYSTEM SIMULATION LOGIC DESIGN

The simulation in this study is a multi-agent simulation based on Anylogic, taking the intersection and confluence mixed conflict taken from the real scene of the mine as shown in Figure 8 as a case. The agent involves high-priority vehicles going uphill, two types of low-priority vehicles that have intersection conflicts and merging conflicts with them, and a cloud-like main agent that carries map, vehicle and other information.



(a)



(b)

FIG 8 – Mixed conflicts of crossing and merging: (a) Mine example; (b) Simulation scenario.

This section mainly studies how to carry out simulation logic design on the intersection conflict coordination traffic strategy between the two vehicles mentioned above, the following model between traffic flows, the gap distance required to realise the gap theory, and the vehicle adjustment method under simple conditions, focusing on describing how to implement the hybrid decision-making of the coordination strategy-following model.

Main agent

The main agent is mainly used to build the simulation scene as shown in Figure 8b, and store, analyse, and execute global instructions. The vertical line in the figure is the driving route of high-priority vehicles, which is consistent with Figure 8a. Intersection conflicts occur first, and then merging conflicts occur.

By setting road node marking monitoring areas, adjustment areas, conflict areas etc, the vehicle size is designed to be 10 m long and 7 m wide, and the road width is designed to be 10 m. The centre of the vehicle is taken as the anchor point, and a safe distance of 40 m is set (that is, a common distance for wide-body vehicles). 30 m safety distance between the front and rear of the vehicle).

The cross conflict area is 20 m horizontally and vertically; in the merge conflict area, the high-priority vehicle conflict area is 20 m, and the midpoint is the merging starting point; the low-priority vehicle conflict area is 50 m, and the midpoint of the high-priority vehicle conflict area is The starting point of the conflict area is 40 m in the opposite direction.

Vehicle agent

The designed initial operating speed of high-priority vehicles is 5.5 m/s (20 km/hr), which is reduced to 4.2 m/s (15 km/hr) in the turning area (merging conflict area), and the speed change process is instantaneous. The vehicle operating status diagram is shown in Figure 9.

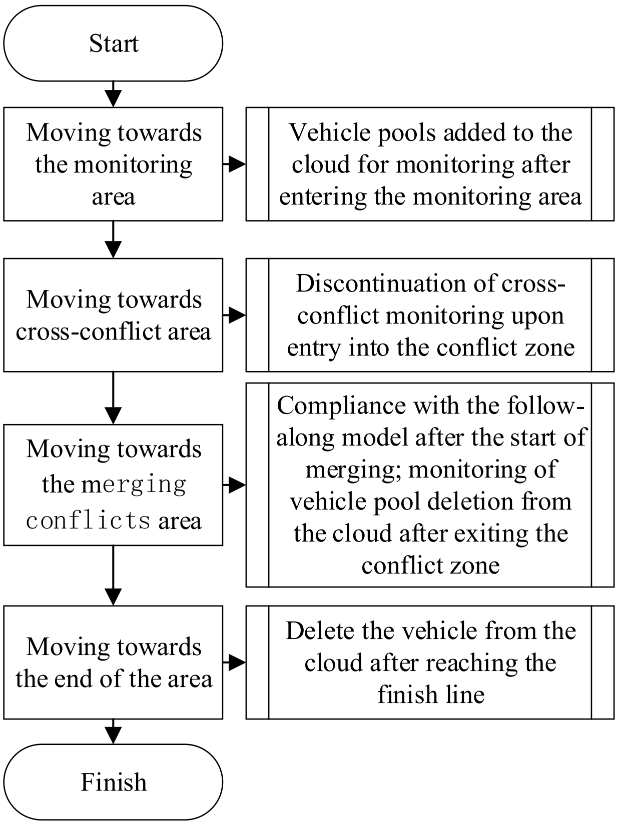


FIG 9 – High priority truck state chart.

The initial operating speed of low-priority vehicles in intersection conflicts and merging conflicts is 7 m/s (25 km/hr), and the vehicle speed change process is instantaneous. The vehicle operating status diagrams are all shown in Figure 10, and the coordination strategy-following model hybrid decision-making methods are different.

The car-following model of all vehicles is consistent. When the gap with the vehicle in front is detected to be less than a safe distance of 40 m, the vehicle will decelerate to 0.9 times the speed of the vehicle in front, otherwise it will continue to accelerate.

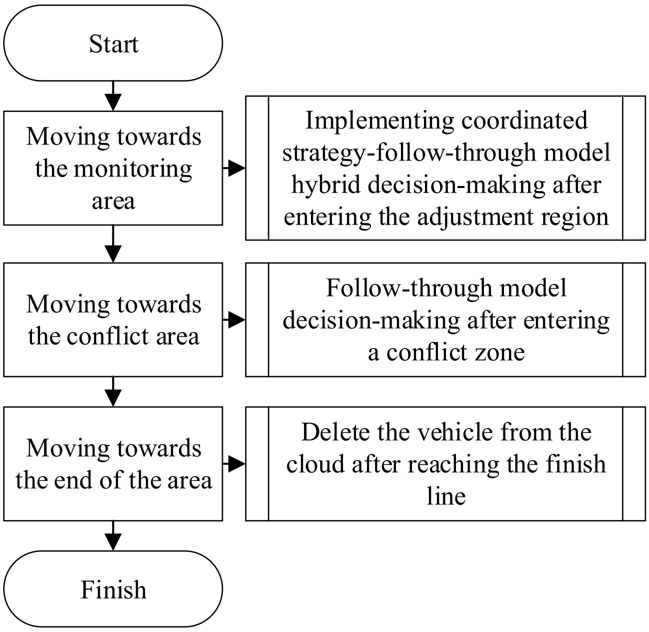


FIG 10 – Low priority truck state chart.

Coordination strategy-following model hybrid decision-making

This part is the key to realising coordinated traffic at the intersection. The coordination strategy and car-following model are programmed with certain logic to achieve hybrid decision-making. The overall design idea is: first determine whether a conflict occurs, and if not, determine whether the car-following model is triggered; if so, first determine whether acceleration is feasible, otherwise decelerate; both acceleration and deceleration decisions consider whether the car-following model is triggered.

The specific implementation process is shown in the form of pseudo code. Table 2 shows the general part of hybrid decision-making, Table 3 shows the pseudo code of cross-conflict hybrid decision-making, and Table 4 shows the pseudo-code of confluence conflict hybrid decision-making.

TABLE 1

Generic section for mixed decision-making.

Input:

HTCEnterNode// High priority vehicle conflict area entry points

LTCEnterNode// Low priority vehicle conflict area entry point

ConflictExitNode// Vehicle conflict area exit point

HTcollection// Store a collection of high-priority vehicles in the monitoring area

gap// Inter-vehicle distance to the vehicle in front

Function definition:

timeTo(point)// time to reach a certain point

distanceTo(point)// distance to a certain point

getSpeed(agent)// Get the speed of an agent

setSpeed(agent)// Set the speed of an agent

agent.Function// Execute Function command on an intelligent agent

TABLE 2

Cross-conflict mixed decision-making pseudo-code.

Algorithm 1: mixed decision-making model for crossing conflicts

```
for i←0 to HTcollection.size()
        do ht=HTcollection.get(i) // i represent the index
        if (ht.timeTo(HTCEnterNode) > timeTo(LTCExitNode)) || (timeTo(LTCEnterNode) >
ht.timeTo (HTCExitNode)) then
                if gap < 40 then
                        vl←lt.getSpeed()
                        vsafe←0.9*vl
                        setSpeed(vsafe)
                else continue
        else vmax=distanceTo(LTCEnterNode)/ht.timeTo(HTCExitNode)
                vmin=distanceTo(LTCExitNode)/(ht.timeTo(HTCEnterNode)+7.3))
                vb←uniform(vmin, vmax)
                vl←lt.getSpeed() /*speed of leader truck
                va←distanceTo(LTCExitNode)/ht.timeTo(HTCEnterNode)
                gap1←gap+(ht.getSpeed()-va)*timeTo(LTCExitNode)
                        if (va <= 7) && (gap1 >= 40) then
                                setSpeed(va);
                        else if gap < 40
                                vsafe=min(0.9*vl, vb);
                                setSpeed(vsafe);
                        else setSpeed(vb);
```

TABLE 3

Merging conflict mixed decision-making pseudo-code.

Algorithm 2: mixed decision-making model for merging conflicts

```
for i←0 to HTcollection.size()
        do ht=HTcollection.get(i) // i represent the index
                n=get_Main().LTcollection.Index(this)
                lt=get_Main().LTcollection.get(n-1)
                f (HighPriorityTruck is in the conflict area) then
                if timeTo(LTCEnterNode) > ht.timeTo(ConflictExitNode) then
                        do continue
                else vb=distanceTo(LTCEnterNode)/ht.timeTo(ConflictExitNode)
                setSpeed(vb)
        else
                if (ht.timeTo(HTCEnterNode) > timeTo(ConflictExitNode)) ||
(timeTo(LTCEnterNode) > ht.timeTo(ConflictExitNode)) then
                        if gap <= 40 then
                                vl=lt.getSpeed()/*speed of leader truck
                                vsafe=0.9*vl
                                setSpeed(vsafe)
                        else atimeToLTC1=distanceTo(LTCEnterNode)/7
```

```
                atimeToLTC2=distanceTo(ConflictExitNode)/7
                 if (timeToHTC1 > atimeToLTC2) || (atimeToLTC1 > timeToHTC2)
        then
                setSpeed(7)
        else continue
    else vb=distanceTo(LTCEnterNode)/ht.timeTo(ConflictExitNode)
        va=distanceTo(ConflictExitNode)/ht.timeTo(HTCEnterNode)
        vl=lt.getSpeed()
        if gap <= 40 then
                vsafe=min(0.9*vl, vb)
                setSpeed(vsafe)
        else if va <= 7 then
                set Speed(va)
        else setSpeed(vb);
```

RESULTS AND DISCUSSION

The simulation uses the initial gap distance of vehicles as the main control variable, macroscopically, the hourly traffic flow density at the intersection as the main evaluation index, microscopically, the vehicle speed and gap change as the main evaluation index, and uses the test results when there are no high-priority vehicles as the main evaluation index. Control group. The monitoring frequency of the system is ten times/second.

When high-priority vehicles are 80–100 m away from the birth point, new vehicles are randomly generated. Low-priority vehicles use a safe distance of 30 m (the distance between the front and rear of the car) as the measurement unit. The cross-conflict test is two to four times the safety distance. The vehicle gap is merged. In the conflict test, the vehicle gap was three to five times the safety distance, and the initial gap fluctuated up and down at 0.2. The control group and the test group conducted five random tests respectively. The test time was 1 hr in real time. At the end of the test, the speed and gap changes of some continuous vehicles that had passed the intersection or merging point were recorded. The overall test parameters are shown in Table 5.

TABLE 4

Gap parameters for testing.

Safety distance multiple	Fluctuation	Gap lower limit	Upper limit of gap	Applicable tests
2	0.2	48	72	cross conflict
3	0.2	72	108	cross conflict; confluence conflict
4	0.2	96	144	cross conflict; confluence conflict
5	0.2	120	180	confluence conflict

The maximum and minimum values of each test result vary within ±4 cu/hr (vehicles/hr), and the test results are the average of five random tests. The test results are shown in Figure 11. The traffic flow density of the test group is slightly smaller than that of the control group, and the difference is less than 10 cu/hr. This shows that after applying the gap theory, intersection conflicts and merging conflicts have minimal impact on the traffic flow density, and can effectively improve the intersection Traffic efficiency.

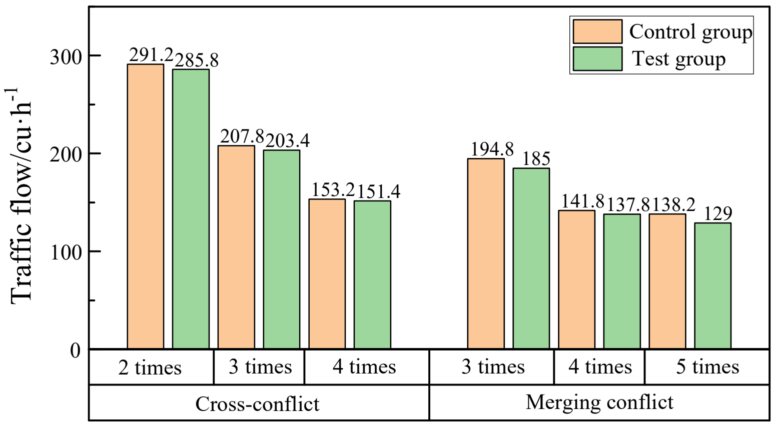


FIG 11 – Test results.

From a microscopic perspective, the driving speed and vehicle gap changes of low-priority vehicles are analysed. Figure 12 shows the speed and gap change curves of intersection conflict coordination vehicles under different vehicle spacings. It can be seen from the figure that low-priority vehicles are under the action of the coordination model-following model hybrid decision-making strategy. When an intersection is detected, In the event of a conflict or car-following conflict, the vehicle speed can be automatically adjusted. As shown in Figure 12a, when the vehicle gap of vehicle #1 is reduced to 40 m, it automatically decelerates and adjusts the vehicle gap according to the speed of the vehicle in front; the increase in the gap between vehicle #3 and vehicle #2 indicates that a cross conflict is detected, and the vehicle decelerates proactively to achieve coordination of passage.

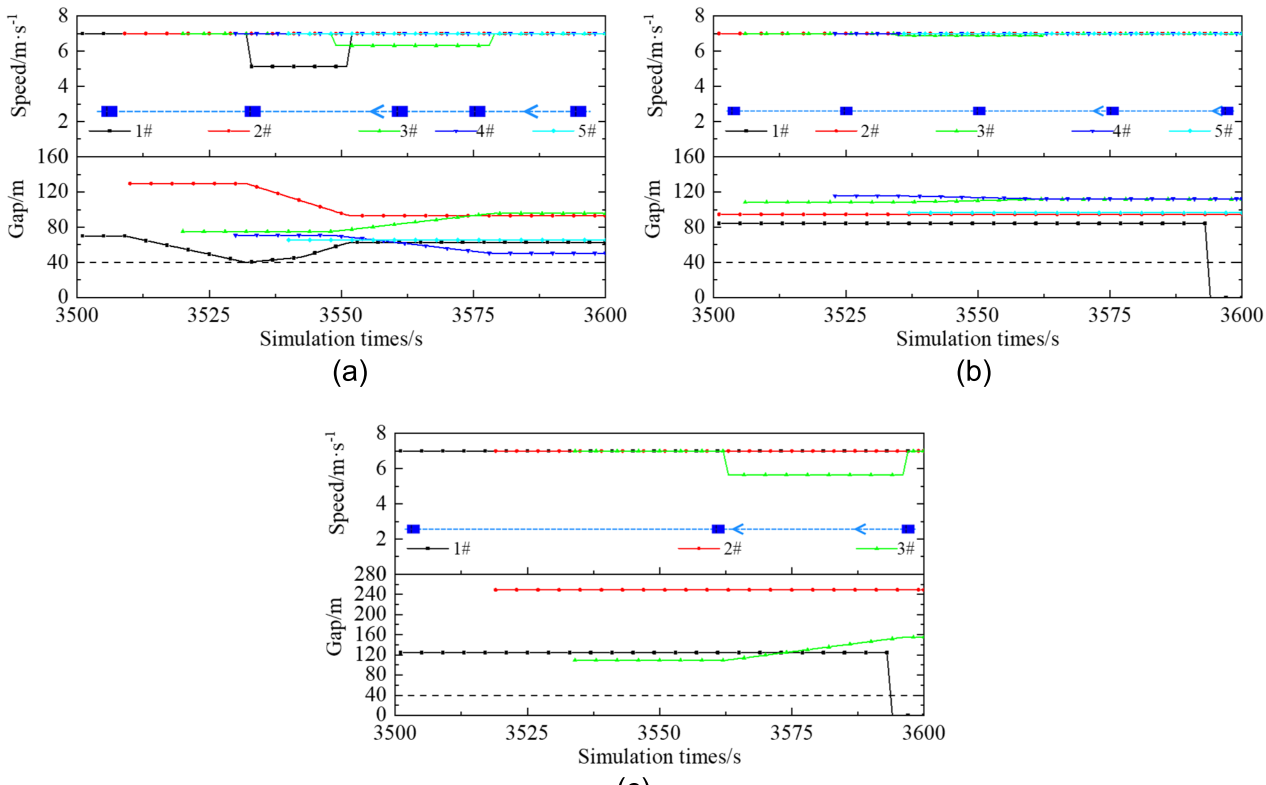


FIG 12 – Cross-conflict coordination access test: (a) Two times the safety distance; (b) Three times safety distance; (c) Four times the safety distance.

Comparing Figure 12, since the vehicle gap in (a) is relatively small, there is a phenomenon that the gap reaches a safe distance. Affected by the car-following model, the vehicle gap changes more frequently, (b)–(c) is relatively stable, indicating that the gap reaches a safe distance, indicating that when the gap reaches three times the safe distance or more, the adjustment of the vehicle speed by the gap theory will basically not trigger the car-following model.

Figure 13 shows the speed and gap change curves of merge conflict coordinated vehicles under different vehicle spacings, in which green vehicles are low-priority vehicles and yellow vehicles are high-priority vehicles. Comparing Figure 13, the minimum initial gap between vehicles in (a) is three times the safety distance. When the yellow vehicles merge, for example, the gaps between vehicles 1# and 3# suddenly drop to 40 m. In the following phenomenon, the speed of vehicles is adjusted more frequently to ensure a safe distance. Vehicle No. 4 even experienced a sudden drop in speed. If factors such as dynamics are taken into account in the vehicle adjustment process, cross traffic based on gap theory may not be possible at three times the safe distance. (b)(c), the speed adjustment frequency drops significantly, and the gap is rarely smaller than the safe distance. This shows that when the gap reaches four times the safe distance or more, the adjustment of the vehicle speed by the gap theory will basically not trigger the car-following model.

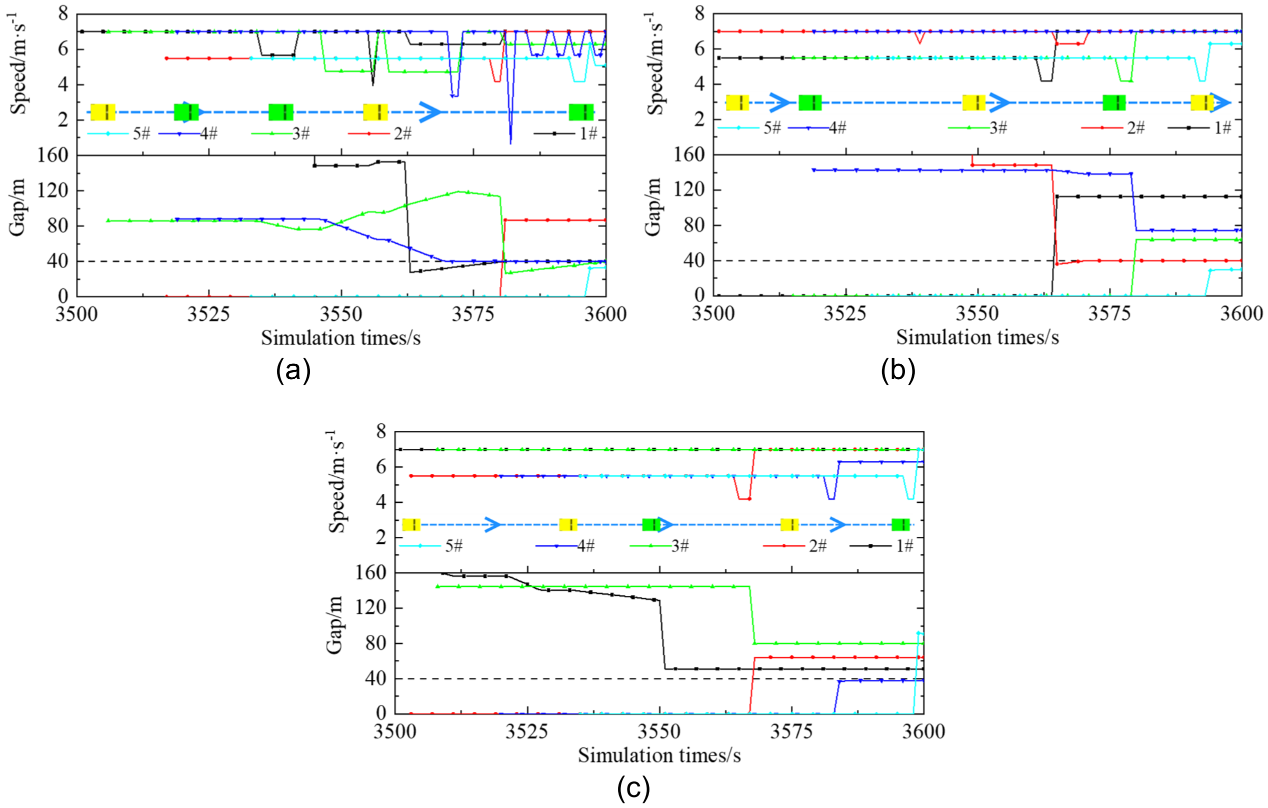


FIG 13 – Merging conflict coordination access test: (a) Three times safety distance; (b) Four times safety distance; (c) Five times safety distance.

In summary, the intersection coordination model based on gap theory proposed in this study can effectively improve the intersection's traffic capacity from a macro perspective and approach the traffic capacity without conflict; from a micro perspective, the proposed coordination model can effectively adjust The main impact of vehicle and coordination conflicts is that when the vehicle gap is relatively small, it is greatly affected by the car-following model and vehicle adjustments are more frequent. Based on production experience, traffic flow density is one of the factors that affects transportation efficiency. It reflects that by transforming large-load mining trucks to reduce the number of unmanned equipment and reduce interference between equipment, intersection conflicts can be reduced and vehicle traffic capacity at intersections can be improved. One of the ways to successfully achieve driverless driving in open pit coalmines.

CONCLUSION

- Intersection conflicts in open pit coalmines are mainly divided into intersection conflicts and merging conflicts. Coordinated traffic is the process of low-priority vehicles giving way to high-priority vehicles.
- The core of the coordinated traffic strategy is to adjust vehicle speeds so that only one vehicle exists in the conflict area at the same time. Car-following behaviour is an important factor affecting coordinated traffic, and vehicle gap distance is an important factor affecting car-following behaviour.
- Under the simulation conditions of this article, when the initial average vehicle gap reaches three (four) times or more of the safe distance, the coordinated traffic performance of intersection conflicts (merging conflicts) is better, and the intersection traffic capacity is close to the traffic capacity when there is no conflict, and the vehicle Adjustments are less frequent.
- Traffic flow density is one of the factors that affects transportation efficiency. By transforming large-load mining trucks, reducing the number of unmanned mining trucks and reducing interference between equipment, it is a way to reduce intersection conflicts and improve the vehicle traffic capacity of intersections.
- By establishing a right-of-way allocation mechanism, the research results can be extended to other intersection access scenarios; considering vehicle dynamics, unmanned vehicle control systems, and other influencing factors, testing feedback to correct intersection coordinated access strategies is a research direction for further realising the preparation of field applications.

ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Foundation of China (51574222).

REFERENCES

Ashtiani, F, Fayazi, S A and Vahidi, A, 2018. Multi-intersection traffic management for autonomous vehicles via distributed mixed integer linear programming, *2018 Annual American Control Conference (ACC)*, IEEE, pp 6341–6346.

Bashiri, M and Fleming, C H, 2017. A platoon-based intersection management system for autonomous vehicles, *2017 IEEE Intelligent Vehicles Symposium (IV),* IEEE, pp 667–672.

Čakija, D, Assirati, L, Ivanjko, E and Cunha, A L, 2019. Autonomous intersection management: A short review, *2019 International Symposium ELMAR*, IEEE, pp 21–26.

Chai, L, 2018. Intersection Slots Coupling Operational Control Method of Intelligent Vehicle Infrastructure Cooperative Systems, PhD thesis, Beijing Jiaotong University, Beijing.

Fayazi, S A, Vahidi, A and Luckow, A, 2017. Optimal scheduling of autonomous vehicle arrivals at intelligent intersections via MI L P, *2017 American control conference (ACC)*, IEEE, pp 4920–4925.

Fu, E, Li, G and Di, S, 2022. Unmanned driving technology and system architecture in open-pit mines, *Coal Engineering*, 54:34–39.

Jiang, H, Yao, Z and Jiang, Y, 2022. Vehicle Schedule Optimization Model for Autonomous Intersection Based on Virtual Platoon, *China Journal of Highway and Transport*, 35:291–303.

Krauß, S, 1998. Microscopic modeling of traffic flow: Investigation of collision free vehicle dynamics.

Li, K, Dai, Y, Li, S and Bian, M, 2017. State-of-the-art and technical trends of intelligent and connected vehicles, *Journal of Automotive Safety and Energy*, 8:1–14.

Mihály, A, Farkas, Z, Zsuzsanna, B and Gáspár, P, 2021. Performance analysis of model predictive intersection control for autonomous vehicles, *IFAC-PapersOnLine*, 54:240–245.

Németh, B and Gáspár, P, 2021. Design of learning-based control with guarantees for autonomous vehicles in intersections, *IFAC-PapersOnLine*, 54:210–215.

Németh, B, Gáspár, P, Szőcs, D and Mihály, A, 2018. Design of the optimal motions of autonomous vehicles in intersections through neural networks, *IFAC-PapersOnLine*, 51:19–24.

Pan, F, Zhang, Y, Zhang, L, Yang, J and Yang, X, 2022. Intelligent Control Strategy of Intersection Based on Gap Theory under Vehicle-Infrastructure Cooperative Environment, *Journal of Chongqing Jiaotong University (Natural Science)*, 41:44–52.

Sun, J, Zhang, R, Jia, H, Wang, T, Cheng, P and Ma, X, 2020. Research and key issues on intelligent development of surface coal mines in China, *Coal Engineering*, 52:16–22.

Sun, N, Wu, W, Zhao, F, and Xiao, G, 2022. Vehicle scheduling AT unsignalized intersections based on enhanced Dijkstra algorithm, *Application Research of Computers*, 39(1):188–193.

Wang, Z, Xin, F, Song, B, Zeng, X, Liu, Y, Wang, J, Tian, F, Zhao, M, Li, J and Li, S, 2022. Overall design of intelligent construction in open pit coal mines, *Coal Science and Technology*, 50:37–46.

Wuthishuwong, C, Traechtler, A and Bruns, T, 2015. Safe trajectory planning for autonomous intersection management by using vehicle to infrastructure communication, *EURASIP Journal on Wireless Communications and Networking*, pp 1–12.

Yan, F, Wu, J and Dridi, M, 2014. A scheduling model and complexity proof for autonomous vehicle sequencing problem at isolated intersections, in *Proceedings of 2014 IEEE international conference on service operations and logistics and informatics*, IEEE, pp 78–83.

Zhang, R, Mao, S, Zhao, H, Guo, S, Jia, H, Zhao, X, Sung, J, Wang, Q, Li, L and Ma, Y, 2019. Framework and structure design of system construction for intelligent open-pit mine, *Coal Science and Technology*, 47:1–23.

Zheng, Y, 2020. Research on Cooperative Vehicle Control Algorithm for Unsignalized Intersection under Connected Vehicles Environment, PhD thesis, Jilin University, Jinlin.

In data, we trust – navigating through the age of AI in the mining industry

R Chandramhan[1], M Pyle[2] and G Lane[3]

1. FAusIMM, Global Technical Director – Operations Optimisation, Ausenco, Vancouver, BC V6E 3S7, Canada. Email: rajiv.chandramohan@ausenco.com
2. MAusIMM, Chief Technical Officer, Ausenco, Brisbane Qld 4000. Email: matt.pyle@ausenco.com
3. FAusIMM, Principal Consultant, Ausenco, Brisbane Qld 4000. Email: greg.lane@ausenco.com

EXTENDED ABSTRACT

Data is the most valuable commodity in the information age. The use of data enables productivity, opportunity, and safety in various sectors and industries. In the late 1950s, Alan Turing coined the term artificial intelligence (AI) to describe the ability of computing machines to think and behave like humans through simplified reasoning and logic (Turing, 1950). This concept of mimicking human behaviour is the building block of machine learning algorithms used in most AI software. The 'learning' aspect in machine learning requires data, that is, information on the environment or the objective, to be modelled or predicted using AI.

An AI-enabled system aims to predict the unknown faster and intuitively. Intuition in software algorithms can be described as probabilistic, learned through the data that the AI system is trained on; indeed, the AI software cannot predict the future, but it can provide the likelihood of an event/action occurring, thereby enabling decisions or responses to prevent it or take action.

Just as various industries have adopted AI as the tool of choice to seek new opportunities (examples: medical research, self-driving cars, financial modelling), the mining industry, too, has been receptive to embracing AI for problem-solving and maximising the value of its business.

In modern mining plants, the accessibility and analysis of extensive data sets have significantly increased, facilitated by customised sensors and powerful computing to provide valuable insights. These insights are gained from a combination of detailed simulation models (digital twins) and operational data analysis. FIG **1**, highlights the interdependency of the data in mining.

There are three areas where machine learning is used:

1. Exploration – to enhance the predictability of valuable minerals.
2. Design – to enable faster development of cost-effective projects.
3. Operations – predict the performance of operating assets.

There are several machine learning tools used widely in the exploration (example: Micromine) in design (example: Autodesk's AI tools for smart designs) and in operations (most instrumentation providers, such as ABB, Siemens, Yokogawa, Honeywell etc). These AI systems are bespoke and have been developed to solve specific problems or tasks. Identifying value and opportunities for the mining business requires connecting the data from various sources to understand its impact on the whole business, community, and environment. To develop an integrated AI solution, 'big picture problem' statements are required, such as:

- How can we maximise the value of mining projects by minimising the greenhouse emissions footprint for the life of the mine?
- How can we build a cost-effective, energy and water-efficient mine?
- Can we predict the future risks and operate sustainably in the face of commodity pricing fluctuations, changing ESG metrics and taxes, and the supply and demand for minerals?

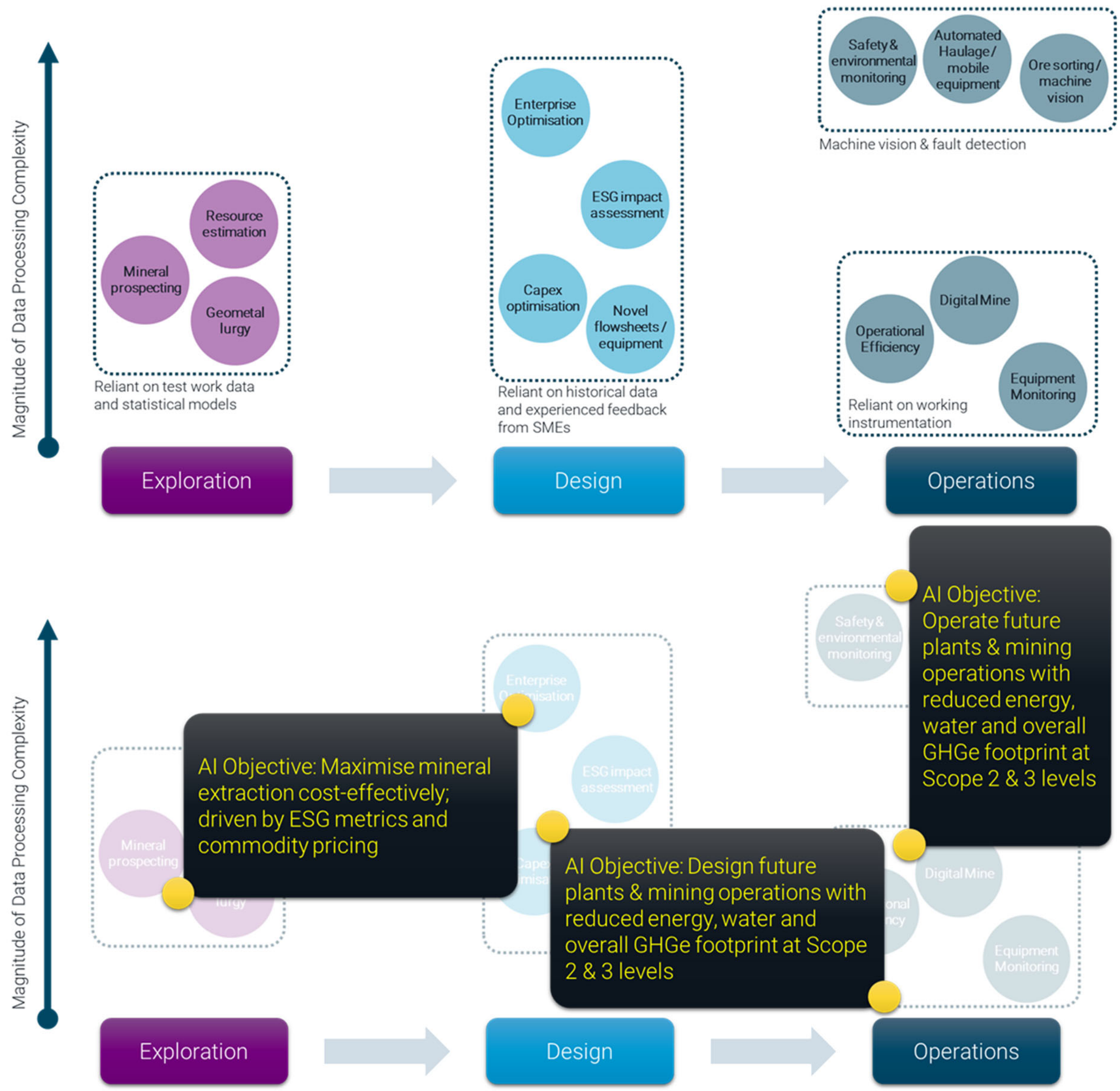


FIG 1 – Examples of AI applications in the mining industry (Chandramohan and Meinke, 2023).

One of the critical challenges to training the algorithms in machine learning models is the availability of good data representing the orebody and reliance on working instrumentation that is properly calibrated to provide the correct process outputs. The mining block is a statistical inference based on the spatial location and orientation of the drilled core samples. As shown

Table 1, the defined block model establishes the value of a mining business through ore characterisation. Using this data, projects can be developed through investment, optimised fit-for-purpose flow sheets can be built to maximise the net present value of a project, and cash flow can be increased through optimised energy and water consumptions, and operating costs.

TABLE 1

Source of data, application and errors.

	Exploration	Design	Operations
Machine learning objective	• Predict the volume of resources and metal grades in the prospected land	• Predict a cost-effective mineral processing flow sheet • Minimise capital cost and footprint • Fast track project development • Predict the mining method and sequencing to maximise revenue	• Predict the performance of asset for the life-of-mine • Predict equipment utilisation, availability • Predict the constraints • Predict productivity (throughput and recovery) • Enhance safety • Predict cash flow ($/t) • Predict ESG impact
Data source	• Drill hole data • Test work data	• Historical projects • Mine life schedule	• Instrumentation • Resource information in the block to predict throughput and recovery
Data resolution	• Meters • Cubic metres	• Cost estimate at various phases of the project development	• Seconds to milliseconds
Source of error	• Sampling/QA-QC • Test work procedures, interpretation of the data • Statistical inference of the block (averaging)	• Capital cost estimation from previous projects • Price variation • Mine plan schedule and ore source	• Instrumentation – calibration • Resource block averaging (sampling, test work data)
Data importance	• High	• Medium	• High
Data impact	• Value of resource = investment for project development	• NPV of the project	• Cash flow, GHGe reductions

The mining block's resolution can be increased using process plant operating data and online ore characterisation sensors (FIG). Leveraging AI, the resolution of the processed mining block can be increased by reducing the volume detail from 10 m^3 to 1 m^3. This method of block model integration requires further validation using measured metallurgical or characterisation through test work analysis.

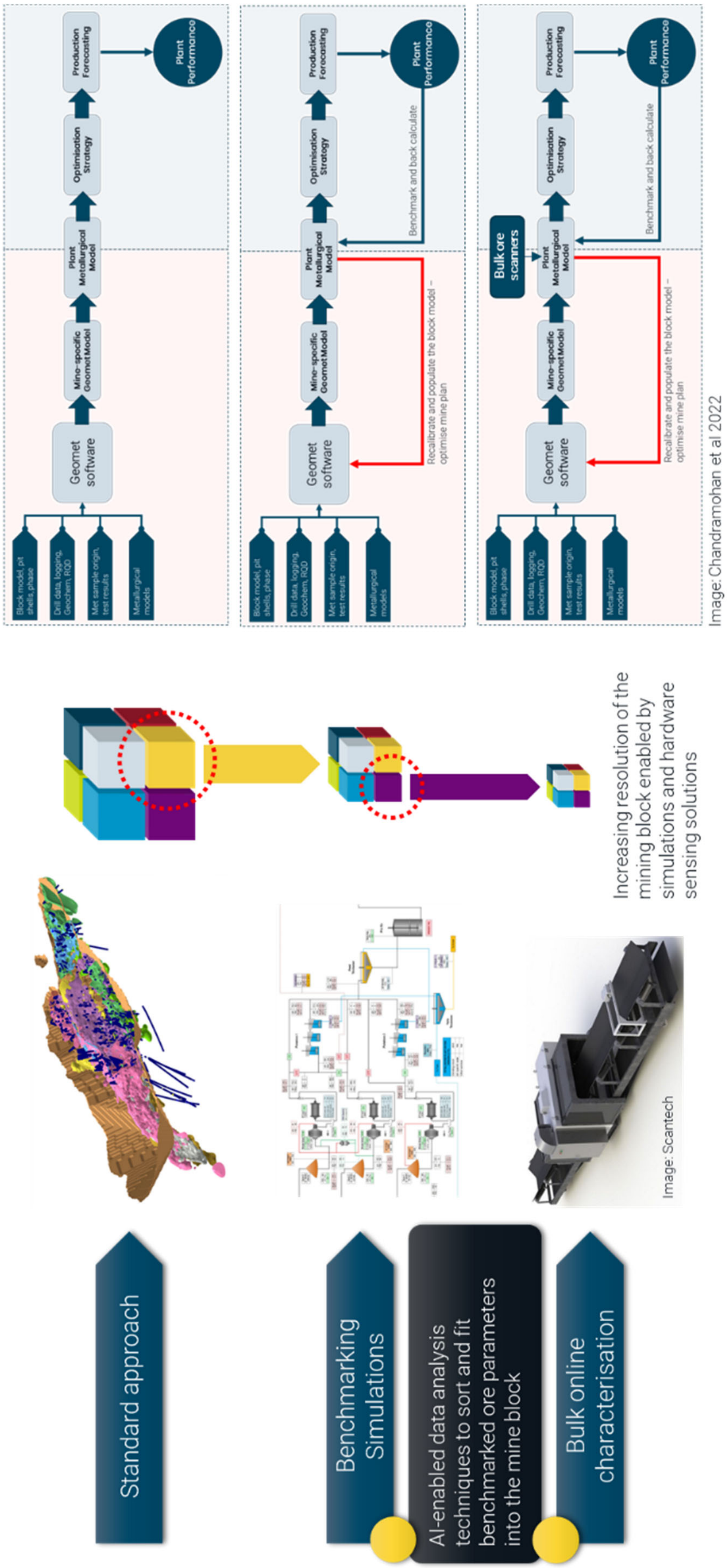


FIG 2 – Increasing the resolution of the mining block (Chandramohan and Meinke, 2023).

Working instrumentation installed in an operating mine is critical to the AI algorithm's model predictive training (FIG). The standard instrumentation is often susceptible to drift or errors in data due to the demanding process conditions. Working sensors and instrumentation are pertinent to assessing the performance of the process and assets. Constraint prediction relies on simulations and digital twins, where the simulation models are benchmarked and trained using the instrumentation data captured from the process and assets.

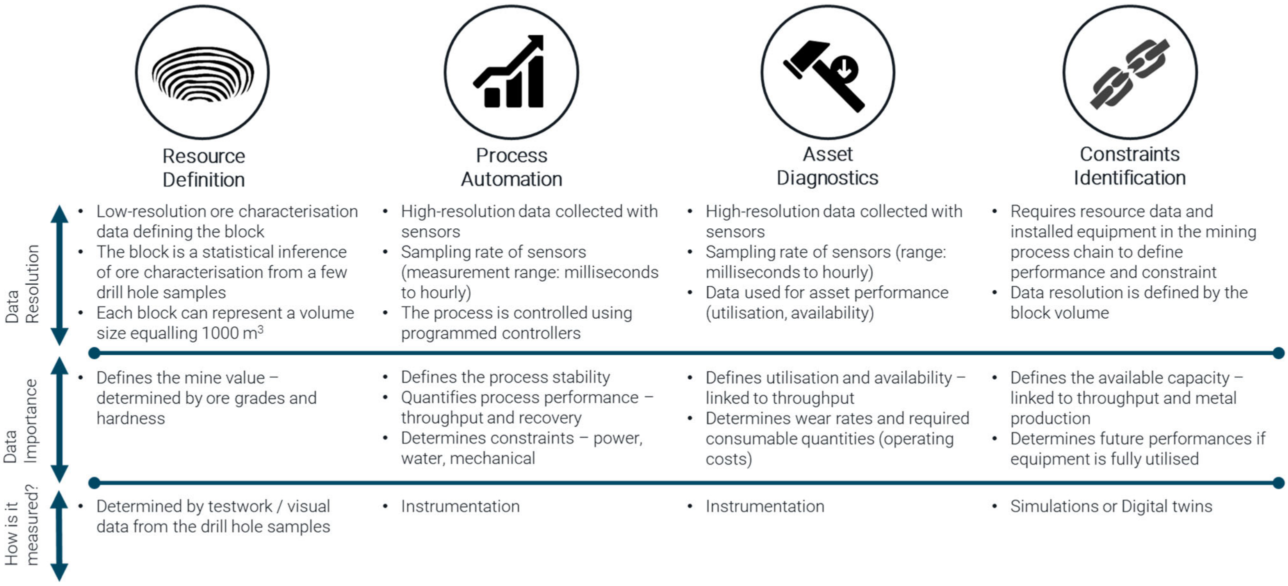


FIG 3 – How data is measured in operations (Chandramohan and Meinke, 2023).

This paper explores the challenges of developing advanced Artificial Intelligence algorithms in mining, especially when the quality of the sourced data that is used for training can be poor or erroneous. The following focusing topics are addressed in the paper and presentation:

- How do you build a robust AI model for mine optimisation?
- How can various data sources be leveraged to minimise sensor errors and calibrate instrumentation?
- What does the mine of the future look like?

REFERENCES

Chandramohan, R and Meinke, C, 2023. The Value of AI in Mining, presented at the World Mining Congress 2023, ICMSAUST.

Turing, A, 1950. Computing Machinery and Intelligence, *Mind,* 49:433–460.

Using machine learning to make smarter screening media maintenance decisions

M Cutbush[1], J Herd[2], J Rowe[3] and F Aziz[4]

1. Product Manager – Digital, Sandvik Rock Processing Australia Pty Ltd, Heatherbrae NSW 2324. Email: matt.cutbush@sandvik.com
2. Lead R&D Digital Engineer, Sandvik Rock Processing Australia Pty Ltd, Heatherbrae NSW 2324. Email: jeremy.herd@sandvik.com
3. R&D Digital Engineer, Sandvik Rock Processing Australia Pty Ltd, Heatherbrae NSW 2324. Email: jacob.rowe@sandvik.com
4. R&D Digital Engineer, Sandvik Rock Processing Australia Pty Ltd, Heatherbrae NSW 2324. Email: fayeem.aziz@sandvik.com

ABSTRACT

WearApp provides expertise for assessing the degradation of removable screening media panels on vibrating screens right in a user's pocket. Through the WearApp application, users can simply take a picture of a panel using their mobile, enter some basic information and have the application assess the wear to provide a recommendation for whether the panel needs to be replaced.

Where traditional mechanisms for assessing panel wear only measure a few points across the panel face and rely on having personnel with specialised knowledge available to perform the assessment, WearApp uses deep learning models to analyse the entire panel face and support the user to make an informed decision.

The application works through analysing a panel image and using a model to automatically detect the corners of the panel. Given the known dimensions of the panel, this enables the application to calibrate the pixel size against a known reference. A second set of models then detect the apertures and measure their dimensions. With the aperture dimensions defined the application assesses the wear of the panel through referencing a stored 3D model of the aperture. Finally, the data from each aperture is collated and the wear of the entire panel face defined.

Since WearApp performs measurement of the entire panel face, it also allows the user to perform a more detailed analysis of the panel's wear profile. Where typically, the panel wear is only measured in a few locations, WearApp's analysis enables users to visualise the panel wear across the entire panel face, identifying areas of high wear that could be leading to premature panel replacement.

Additionally, because the entire panel face is measured the change in screening efficiency can be calculated accurately for the worn panel, even taking into account the impact of aperture pegging by small rocks.

INTRODUCTION

Vibrating screens are a critical component of most mining operations. They are typically used in the processing plant to separate bulk material into required size fractions for further processing and subsequent sale. The vibrating screen surface that the bulk material makes contact with are modular consumable components, commonly referred to as screening media or 'panels'. These panels are used to separate the bulk material and come in various sizes and material of construction.

The screening media panels have holes, commonly referred to as apertures, which are used to allow certain sizes of the bulk material to pass through them. There has been significant investment in research to optimise the shape and surrounding structure of the apertures, to maximise their service life while remaining effective in separating the bulk material as they wear.

Typically, screening media panels on vibrating screens are assessed for wear or various failure modes during each shutdown by personnel climbing onto the vibrating screen and manually measuring the remaining panel material using a slide rule or similar manual measurement tool. Due to the conditions on the screen, such as dust and debris, high temperatures and low head room (sometimes only having 300 mm between screening decks), measurements are typically performed at a single point on the panel and often only on a selection of panels on the deck.

To alleviate the effort of conducting panel wear measurements, WearApp has been developed. WearApp, supporting access through the user's mobile phone, calculates the wear and remaining service life of a panel through a single image. Through the use of WearApp, operators can increase the detail of the wear analysis of the vibrating screen media, measuring the panel's wear at each aperture rather than at a single point. Additionally, with the time saved from conducting manual measurements, operators can analyse more of the deck, completing a more in-depth analysis of the wear profile along the screen.

BACKGROUND

Screening and panel wear

A vibrating screen is a precision apparatus designed to separate small particles from larger in sizing and scalping applications or separate water and very fine particles from the material stream in applications such as dewatering. Regardless of the application, material presented to the screen moves across a perforated deck consisting of screening media panels with an array of apertures through to the lower decks or collection points (Figure 1).

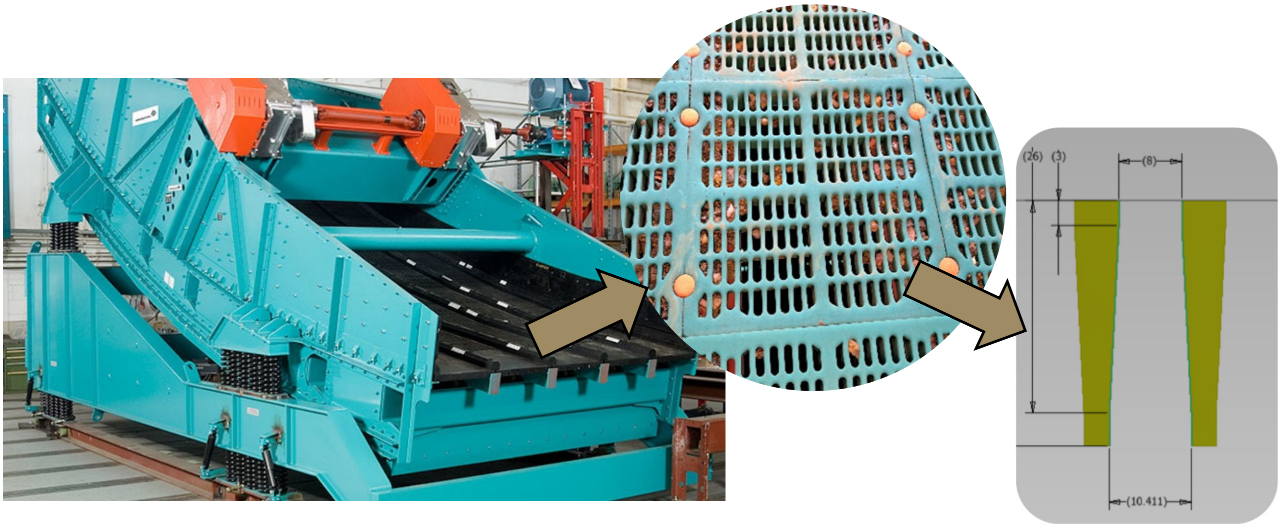


FIG 1 – Vibrating screen (left), consisting of screening media panels (centre) featuring apertures (right) for material separation.

These panels are made from a range of materials with the most common being injection moulded rubber or polyurethane or from stainless steel meshes. Additionally, panels exhibit a spectrum of sizes and accommodate various aperture shapes, including slot, square, and zigzag (variable relief) configurations, each tailored with different dimensions to optimise the screening process for both the feed material and the specific requirements of customers.

Over time, the abrasive feed material leads to panel wear, whereby the surface of the panel is worn down until they are eventually worn through. To avoid this, panels are regularly inspected to measure their remaining thickness or 'working depth'. Once the working depth exceeds a critical threshold defined by the panel material, feed material and application, it is replaced with a new panel.

Conventional panel assessment procedures are conducted by qualified technicians through visual inspection to identify panels exhibiting the most conspicuous signs of wear or apparent defects. A select number of apertures from the most deteriorated sections of these panels are then measured for the remaining working depth utilising a variety of precision hand tools such as feeler gauges and rulers. Advice from those with subject matter expertise is that working depth measurements taken *in situ* are typically accurate to within ±2 mm. Given the limited number of panels scrutinised and the utilisation of imprecise hand tools, a conservative approach is generally adopted, often resulting in premature removal of panels that might otherwise endure until the following site shutdown.

Aperture wear indicators

Several advancements have been made in the identification of panel wear, introducing distinct features into panel designs which become apparent as a panel wears. Such improvements include aperture shape change indicators where slot shaped apertures transition to rectangular forms, or through embedding blind pin holes that are presented on the panel surface at various working depths.

Similarly, some indicators are introduced due to manufacturing techniques. For example, as an artefact of manufacturing panels through injection moulding, panels exhibit relief angles in the apertures resulting in them tapering through their service life. This phenomenon causes an enlargement of the effective aperture size as the panels wear down, thereby facilitating the passage of larger particles. This indicator is made use of by WearApp to analyse the panel wear.

METHODOLOGY

WearApp utilises two machine intelligence modules to analyse a panel photo taken by an operator and uses the results of the analysis to calculate various wear properties including aperture width and depth, current open area and remaining service life.

The first module, corner detection, identifies the bounds of the panel under assessment through identifying the panel corners. The second module, aperture segmentation, identifies the aperture locations and applies a mask to the image to differentiate the panel material from the apertures, debris or mud, or pegged rocks stuck in the aperture structure.

Corner detection

The corner detection module takes a panel image as input and provides the four corner points of the panel closest to the centre of the image. This operation occurs in two stages, employing two deep learning models as depicted in Figure 2.

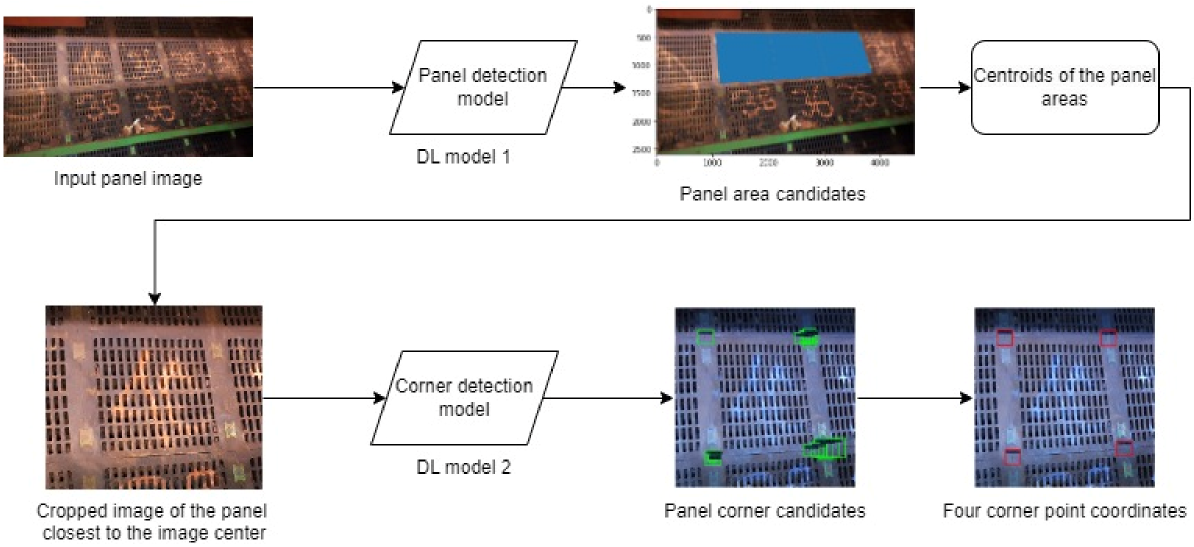


FIG 2 – Corner detection flow diagram.

The first model is trained on images containing photos of panels displayed on a screen as input, with individual panel masks serving as annotations. A single input image can contain one or multiple panels, with annotations representing the masks of individual panel areas.

During training of the model, the cross entropy loss between annotations and model output masks is utilised in backpropagation to optimise the weights, ensuring the production of accurate masks. Subsequently, the centroids of the panels are calculated to detect the panel nearest to the centre of the image. The panel is then cropped with additional pixels extended around the edges to serve as input to the corner detection model.

The second model's inputs are the cropped single panel images with extra padding around the edges to mitigate edge-cutting errors from the previous model. The annotations for the second model consist of coordinates of the four corners of the panel. This model is trained to identify corner candidates for the panel centred in the image, followed by a non-maximum suppression operation to select the best four candidates as the four corners.

Both models are trained on images depicting a range of panel types under various lighting conditions. Training on a diverse range of panel types enables the model to detect corners irrespective of the colour and size of the inputs. The accuracy of the module is calculated based on the detected corner positions within a 10-pixel radius of the ground truth.

Aperture Segmentation

The aperture segmentation module, designed to differentiate the apertures from the panel material or debris, consists of two separate models run in parallel. Whilst collecting images for annotation it was observed in numerous cases that multiple apertures were covered by large rocks or mud, making it difficult to detect individual apertures under the covered artifacts using only segmentation masks. To address this issue, a second deep learning model is implemented to apply a bounding box detection around each individual aperture area. The operation is outlined in the Figure 3.

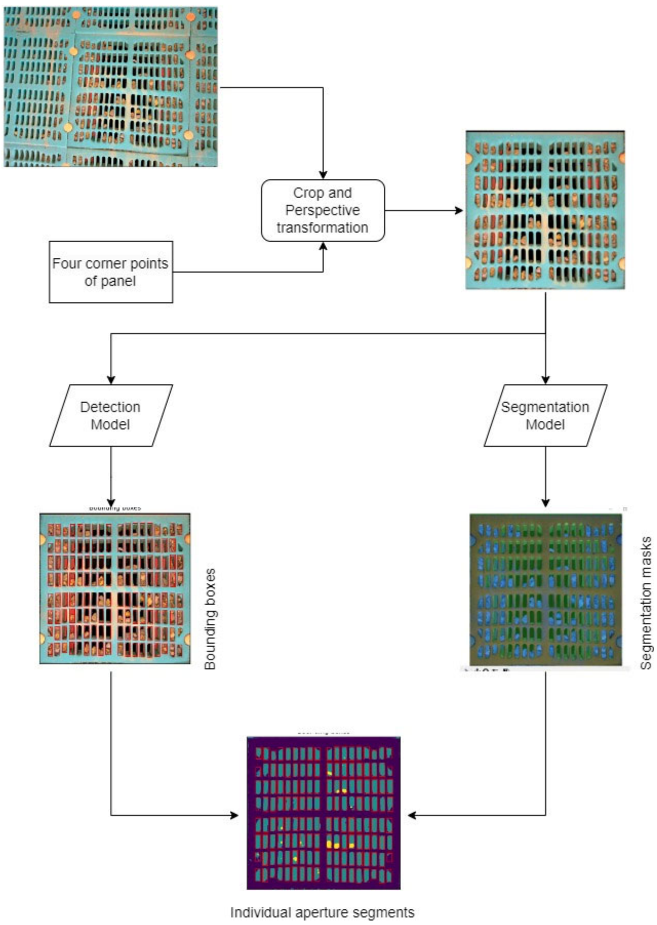


FIG 3 – Aperture segmentation flow diagram.

First, an image of a single panel is cropped from the input photo using the corner coordinates detected by the corner detection module. Next, perspective transformation is applied to straighten the image, ensuring panel corners are at right angles and panel width and height are equalised to reference lengths. The transformed image is then fed into both the segmentation and detection models.

The segmentation model identifies the areas of open apertures, debris and pegging, whilst the detection model identifies each individual aperture position. Combining the two outcomes provides the masks of each individual aperture and classified pixels between open apertures and pegging. These classified pixel areas are used to measure aperture width as well as wear amount.

The aperture segmentation module generates segmentation masks for three classes: open aperture, debris and pegging.

A deep neural network model is utilised for segmentation. Training images for are model are manually annotated, classifying pixels into classes: background, open apertures, debris, and pegging. The model is trained to classify each pixel of the image into one of the classes. Cross-entropy between model output and annotations of all pixels in an image is considered as loss in backpropagation for SGD optimisation.

Another deep neural network is employed to detect aperture bounding boxes. Input data sets are manually annotated, where the annotations comprised arrays of the four corner coordinates of the aperture bounding boxes. Each image could contain between 9 and 200 apertures, allowing for a significant training pool from the analysis of relatively few images. The cross-entropy loss between ground truths and the output values is utilised in backpropagation optimisation.

Both models are trained with the same data set but different annotations according to their functionality. Image augmentation techniques such as RGB swap and rotations are employed to add variance to the data set and generalise the model.

MEASUREMENT

After the generation of the segmentation mask and aperture detections, a series of calculations are conducted to derive several key metrics, including:

- aperture width
- depth of wear
- effective panel open area
- remaining life expectancy.

The initial processing stage investigates the segmentation mask for detected apertures with significant pegging. Given that pegging significantly impairs the apertures processing effectiveness, those containing a substantial amount are subsequently excluded from further aperture width and panel wear calculations.

Within the remaining apertures, an inscribed circle is delineated from the contour of each aperture's open area mask, with the resulting aperture width defined as its diameter. Utilising WearApp's knowledge of the size of the panel, measurements in pixels are converted into metric lengths. Upon measuring all apertures, statistical parameters are derived including average and 95th percentile aperture widths. The effective panel open area is ascertained from the open area of each aperture, taking into account pegging.

Employing knowledge of the original aperture width and relief angle, the depth coinciding with the measured width is calculated. By computing wear at each aperture location, a visualisation of panel wear variation across the panel are generated providing insights such as material feed biases.

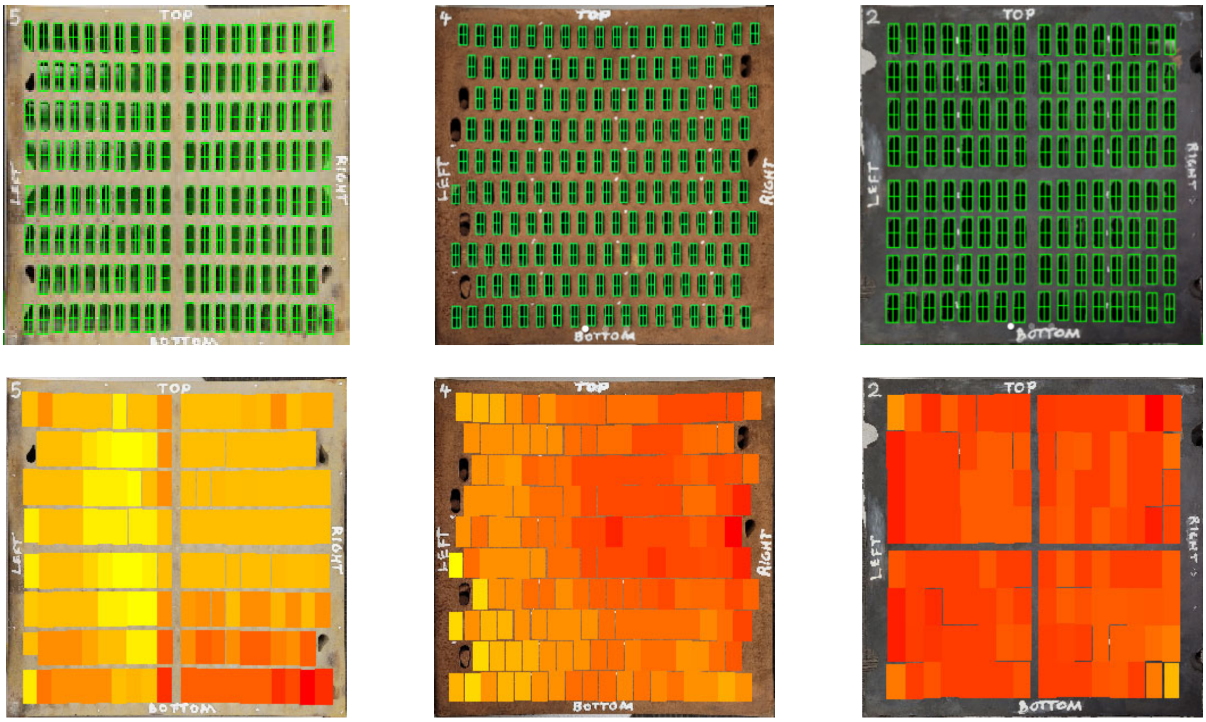
Given a known panel install date from user input or host tool, the wear rate is then computed using the 95th percentile wear measurement. The wear rate is then extrapolated to calculate when the working depth will exceed the critical threshold and a remaining service life calculated.

Typically, the critical threshold encompasses a safety margin to ensure an adequate amount of working depth remains on the panel upon replacement. This safety margin mitigates for a potentially accelerated panel wear rate and increased likelihood of defects occurring as the panel wears down. As a user definable value, the critical threshold enables smarter maintenance decisions through enabling users to tune it for the plant and application requirements.

Due to the enlargement of the effective aperture size as the panels wear down, mentioned in the Aperture Wear Indictor section of the background, the process specifications of the entire screen deck can change as the individual panels wear, passing larger particles than intended. For this reason, some applications focus primarily on aperture width over remaining panel depth as the primary indicator of service life. To this end, the critical threshold can also be used as a safety margin to protect against excessive changes to processing specifications of the screen.

RESULTS

The system's performance is evaluated based on the accuracy of the aperture width measurement compared with the ground truth width. The ground truths of aperture widths were manually measured in a laboratory environment using slide callipers. Three panels are analysed below to demonstrate performance of the application's aperture width measurement and its impact on the panel's depth estimation. These panels differ in type and contain 156, 157, and 128 apertures respectively, as depicted in Figure 4. The images of the panels were processed through WearApp and the statistical data of the widths were compared with the ground truth. The performance comparison is presented in Table 1.



Panel 1 Panel 2 Panel 3

FIG 4 – Panel images used in performance analysis. The top row displays the estimated bounding box with the width and height of the apertures, while the bottom row shows the heatmap of wear amount across the entire panel.

From the visualisation of the results in row 1 of Figure 4, it can be observed that the system detects and calculates the width of the apertures throughout the entire panel, excluding those apertures that are blocked by pegging. From these measurements, the tool ranks the wear amount of the detected apertures and presents the results in a heatmap plot relative to the starting width, as shown in row 2 of Figure 4.

TABLE 1

Performance analysis of WearApp.

Panels	Panel 1		Panel 2		Panel 3	
Starting Aperture Width (mm)	8		8.5		9.5	
Final Aperture Width (mm)	10.41		9.97		11.91	
Available Working Depth (mm)	30		35		30	
Statistics	**Average**	**95th Pctl**	**Average**	**95th Pctl**	**Average**	**95th Pctl**
Manual measurement (mm)	8.52	9.14	9.20	9.77	9.77	10.01
WearApp results (mm)	8.55	9.19	9.26	9.74	9.82	10.17
Measured Width Deviation	1.2%	2.1%	4.1%	-2.0%	0.4%	1.3%
Calculated Depth Error (mm)	0.37	0.62	1.43	-0.72	0.15	-0.08

From Table 1, it can be observed that the discrepancies in the average aperture width from the manual measurements do no exceed 5 per cent of the aperture wear profile, resulting in a maximum error of the calculated depth of 1.43 mm. Similarly, the error in the 95th percentile measurements do not exceed 2.1 per cent of the aperture wear profile and exhibit a maximum error in the calculated depth of 0.72 mm.

A notable feature of using WearApp over manual measurements not captured by table 1 is the time required to capture results. Whilst measuring a single aperture as typically done in practice, on a panel using traditional means can be completed in a matter of seconds once the technician is set-up, measuring each aperture on these panels took close to an hour of dedicated time. Conversely using WearApp to measure every aperture, from the time a photo was taken to observing results only 15 secs elapsed, including an 8 sec period where the user was able to take a photo of another panel and submit it for analysis.

DISCUSSION

As the width of apertures increase through the body of the panel, the depth of the panel can be calculated through knowing the relationship between the two. The result of relying on this relationship is that errors in width measurement also affect the perception of panel depth. Therefore, the observed deviation in widths from the true measurements is directly proportional to the errors in-depth perception.

The WearApp calculation reveals a maximum error of 1.43 mm in-depth calculation. Given the typically challenging access to panels and the adverse environmental conditions such as dust and debris accumulation, manual calculation of aperture width and depth in real-time on-site becomes difficult. The maximum error of 1.43 mm is representative of the acceptable error, ±2 mm, that is experienced through traditional manual measurements. Conversely, the process of measuring the panel was made significantly easier and faster as the technician only needed to take a photo, and the result provided an analysis of the entire panel's wear instead of a single measurement point. This highlights the advantages of employing automated deep learning techniques in WearApp for accurate wear amount estimation and determination of remaining panel life.

FURTHER DEVELOPMENT

As panels are susceptible to various physical defects beyond just reduced working depth, including ligament tears, broken or exposed grids, holes, and faults in fixing systems, an additional detection and classification model will be introduced into WearApp's image processing pipeline. Once integrated a user will not be required to perform any visual inspection or manual measurements to identify panels requiring replacement.

Certain defects can occasionally occur during manufacturing and may be missed during quality assurance testing or only become apparent after panel wear has occurred. Hence, WearApp offers the potential for integration within the manufacturing process, enabling evaluation of every panel without the need for a specialised technician. This integrated process can pre-emptively identify defective panels before they are dispatched to site, ensuring higher quality control standards.

CONCLUSION

The application of machine learning tools through WearApp has enabled development of a tool that can perform measurements of wear and remaining working depth of screening media panels to a similar level of level of accuracy than is typically experienced in the field, whilst significantly reducing the time and effort required to obtain the measurements. The use of machine learning also minimises the risk of human error during this critical maintenance task, which is typically completed in arduous conditions.

Additionally, further development opportunities are available to extend the value offered by this tool to detect additional failures modes outside of wear and to be applied to different areas of the product life cycle.

The WearApp tool provides substantial value to the end user by providing a significant amount of additional information related to the wear and performance of each screening media panel installed on a vibrating screen. The assessment of wear and the impact to the vibrating screen processing performance can now be completed on the entire panel, rather than only a few apertures being measured and assessed by a human. This additional information will allow the mining industry to make smarter decisions on how they execute their screening media maintenance strategies, with decisions now being able to be made on when to replace panels by resulting open area, rather than the aperture wear.

ACKNOWLEDGEMENTS

Thanks goes out to the many colleagues throughout the Sandvik Rock Processing group for the invaluable contributions made to make WearApp a reality. Without the expert input of personnel from R&D, engineering, operations, and service, the development would not have been possible.

Machine learning integration of hyperspectral and geophysical data for improved exploration targeting

R A Dutch[1], T Ostersen[2], B P Voutharoj[3] and M Paknezhad[4]

1. Head of Applied Science, Datarock Pty Ltd, Melbourne Vic 3000.
   Email: riandutch@datarock.com.au
2. Senior Data Scientist, Datarock Pty Ltd, Melbourne Vic 3000.
   Email: thomasostersen@datarock.com.au
3. ML Engineer, Datarock Pty Ltd, Melbourne Vic 3000.
   Email: bhanuprakashvoutharoja@datarock.com.au
4. Senior ML Engineer, Datarock Pty Ltd, Melbourne Vic 3000.
   Email: mahsapaknezhad@datarock.com.au

INTRODUCTION

With the proliferation of new sensor technologies, acquiring multiple data sets over the same ground is becoming cheaper and easier than ever. This new, higher resolution multivariate data provides a significant resource for exploration and resource geologists but comes with the added complexity of effectively integrating the various data sets in useful and meaningful ways to elucidate new geological understanding.

Both geophysical data sets and hyperspectral data are extensively used for exploration targeting, providing different information at different resolutions and crustal scales. One of the biggest challenges comes from trying to effectively integrate data sets that record very different physical properties, across the different scales these data are captured at, in a way which can allow for a data-driven analysis of these combined data sets.

Machine learning techniques can be particularly useful as a means of extracting meaningful information from large data sets and reducing complex multivariate data sets into simpler vector representations of the important features. Here we present an approach using two custom deep learning networks to create a unified feature space, at the same spatial scale, which can learn relationships between the different input data modalities and provide a data set for downstream modelling tasks (Figure 1).

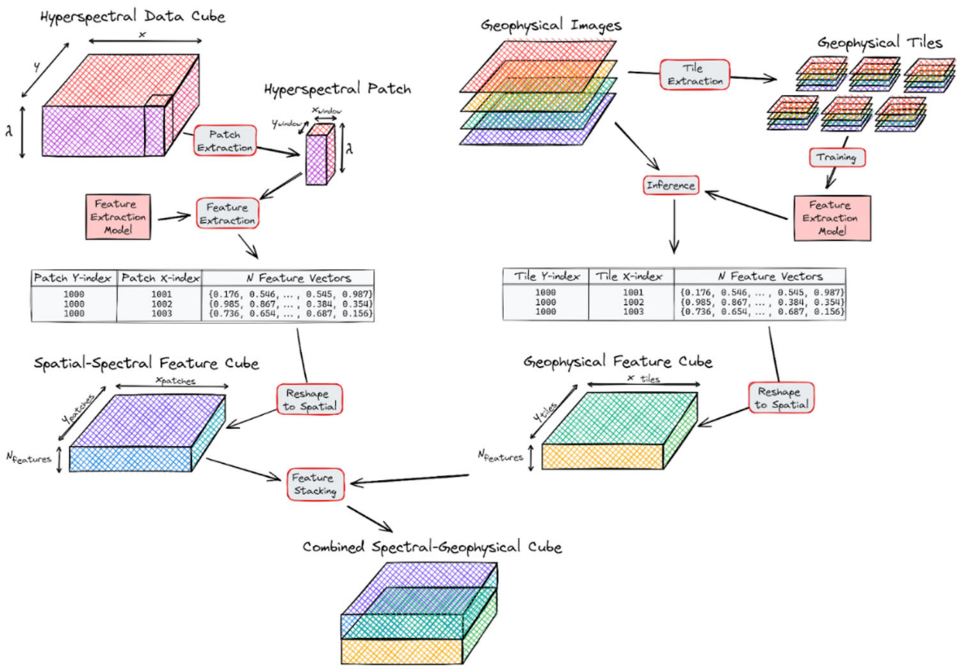


FIG 1 – Conceptual illustrations of the feature extraction procedures used to derive complex information in the form of feature vectors. Combining feature vector information from the two data modalities provided for joint analysis of spectral and geophysical texture information.

HYPERSPECTRAL FEATURES

Hyperspectral imagery data sets capture the intensity of reflected or emitted light across hundreds of narrow contiguous bands of the electromagnetic spectrum. The high spectral resolution of these data record subtle spectral patterns that encode complex information sensitive to the composition and physical properties of the surfaces being imaged.

In addition to the high spectral resolutions, airborne and space-borne hyperspectral data sets are often acquired at higher spatial resolution than is typical for most geophysical data sets. Integrating these data types therefore requires a degree of spatial scaling. There are many ways to do this but most methods don't take the spatial relationships or important compositional data contained in the aggregated spectra into account.

A masked autoencoder (MAE) is an unsupervised learning model that employs two Vision Transformers: one for encoding and another for reconstruction. Originally designed for RGB-based images, the MAE divides an image into fixed-size patches. It works by randomly masking portions of these patches and then passes the unmasked ones to the encoder to extract visible features. These features are then used by the decoder to reconstruct the masked parts of the image during training. By predicting pixel values for masked patches using unmasked features, the decoder learns to reconstruct the image.

Hyperspectral data can have 100s of channels, each capturing unique information such as vegetation, water bodies, and different mineralogical features. The MAE uses vision transformers with a self-attention mechanism that helps learn spatial associations between patches for feature extraction. We have added a spectral self-attention mechanism that operates explicitly on the spectral dimension. This helps the model capture correlations between spectral channels, weight them based on strength, and aggregate information across channels. Additionally, we have included a spectral masking module that masks spectral channels. By leveraging contextual information from unmasked channels, the model predicts values for masked ones, leading to stronger reconstruction.

Using this custom MAE model we can generate robust spectral-spatial feature embeddings at any scale from high-resolution hyperspectral data.

GEOPHYSICAL FEATURES

Geophysical data sets capture different physical parameters from the surface to the crustal scale. These data sets are acquired at varying resolutions from decimetre line spacing to kilometres. An important aspect of geophysical data is not only the raw values of the data itself, but the rich geological information contained in the spatial relationships and textures in the data. Here, again, computer vision techniques allow us to quantify those spatial features in the geophysical data, at a scale of our choosing.

Using a custom multi-channel convolutional neural network (CNN), we extract meaningful textural feature embeddings from a combination of the various geophysical data sets. In a similar way to the hyperspectral model, using self-supervised learning (SSL), the model can learn effective representations of the multi-dimensional data, expressed as 1D numerical vectors.

The specific SSL model used in this case was a modified version of the Swapping Assignments between multiple Views (SwAV) method which takes each input image and applies multiple random cropping procedures to generate a series of different representations of the same image. An encoder then learns that each of these cropped versions represent the same thing, and this is repeated such that patches with similar fundamental characteristics elsewhere are also considered similar. This means the model is robust to learning the similarities and differences between geological structures which become truncated due to the patch-cutting process.

By capturing these feature embeddings at the same spatial scale (ie using the same patch sizes for both models), we can effectively integrate these data sets together in a single unified latent space.

RESULTS AND IMPLICATIONS

Figure 2 presents views of raw hyperspectral imagery, extracted spatial-spectral features and aeromagnetic data acquired around Cloncurry in Western Queensland. Hyperspectral imagery was acquired with the HyMap™ system as part of the Geological Survey of Queensland's Collaborative Exploration Program initiative with Roundoak Minerals (CEI0316). The raw hyperspectral imagery has a spatial resolution of 1.7 m, almost two orders of magnitude higher resolution than Geoscience Australia's total magnetic intensity compilation in the area. To integrate these two data sets, a spectral MAE model was trained on a patch size that matched the native resolution of the aeromagnetic data and used to extract feature vectors across the image. The resulting spatial-spectral feature vectors are presented in dimensionality reduced, composite RGB form in the central plot. Dimensionality reduction to 3D was performed with the non-linear dimensionality reduction algorithm UMAP.

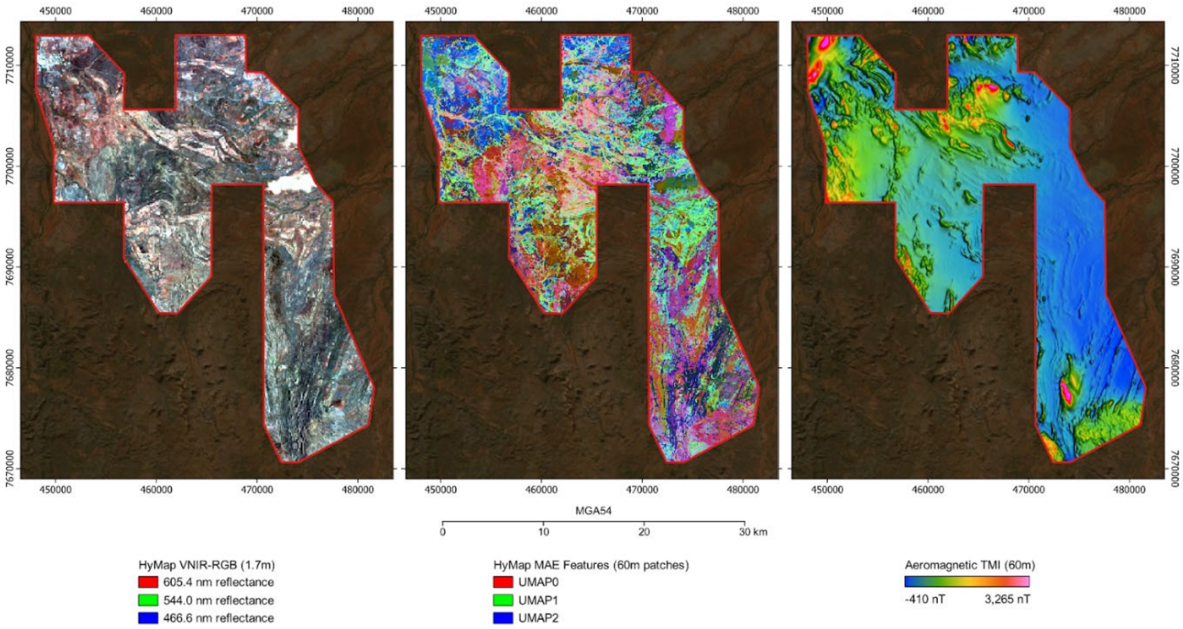


FIG 2 – Views of Cloncurry study area including composite RGB from visible wavelengths in HyMap hyperspectral image (left), dimensionality reduced composite RGB representation of extracted spatial-spectral feature vectors (centre), and total magnetic intensity pseudocolour grid (right).

Spatial-spectral feature vectors extracted by the spectral MAE model effectively capture compositional information from the spectral dimensions, as well as textural information present in the spatial dimensions of the hyperspectral imagery. This is evident in the dimensionality reduced composite RGB of the features shown in the figure above, where green dendritic structures represent vegetated drainage channels. Linear textures in the south of the image delineate changes in weathered surface composition related to underlying geology, where magnetic metabasalts and metadolerites are intercalated with metasedimentary units.

This new approach allows us to bring these disparate data types together to produce robust data-driven prospectivity analysis or target identification based on similarity to other known targets or prospects. This methodology can be used on core hyperspectral imagery, to effectively integrate different types of data sets across an orebody, allowing for a more rigorous assessment of the relationships between properties, and the potential to better understand and model a deposit.

Subtek™ 4D™ – Optimised blasting performance through the application of new underground bulk explosive technology

S Evans[1] and B Taylor[2]

1. Lead Engineer – New Underground Technology, Orica, Perth WA 6007.
   Email: sam.evans@orica.com
2. Senior Manager – Commercialisation, Orica, Kurri Kurri NSW 2327.
   Email: ben.taylor@orica.com

ABSTRACT

Bulk explosive technology for underground mining has not seen any significant technological advances since the widespread transition from ammonium nitrate fuel oil (ANFO) to ammonium nitrate emulsions (ANE) commencing in the 1980s. The in-hole energy profile that conventional ANE systems deliver is limited by the physics of chemical gassing and simple control systems. This compromises the range, precision, and accuracy of energy delivery into the blasthole, and in some cases limits the length of charge that can be delivered. Orica's 4D™ bulk system removes many of these constraints, enabling better blasting performance across all underground mining methods. This paper reviews work completed at three mining operations across Australia, the United States, and Chile with a focus on how this system can improve mining operations and deliver sustained commercial and productivity benefits into the future. These benefits include improved ore recovery, reduced dilution from waste rock, and reduced overall explosives consumption. This paper also reviews how this new technology can be applied for planning future mining operations.

INTRODUCTION

Orica's 4D™ bulk system uses a new, smarter method to control the delivery of gasser and modified emulsion to blastholes. The technology expands the range of average blasthole energy available to designers and gives them new options to control the distribution of energy within blastholes that are impossible to achieve with conventional systems. 4D™ improves drill and blast outcomes in regular production designs and enables novel loading techniques like placing multiple energy products in the same column without multi-pass loading. The application of this technology for development mining and production mining environments and in multiple commodity types is ongoing with trials in Australia, the United States, and Chile.

The conventional bulk loading options for underground mining explosives include ANFO, gassed ANE, and solid sensitised ANE. ANFO is known for its cost-effectiveness and ease of use but is constrained by its limited energy range and lack of water resistance. ANFO can only be pour loaded to give a relative bulk strength (RBS) of 100 per cent, or blow loaded to give an RBS of around 130 per cent. Gassed ammonium nitrate emulsion (ANE) sensitised with a chemical gassing agent offers a greater range of energy and better water resistance, but hydrostatic pressure changes the density and energy of the column with depth, especially in downholes. Conventional delivery systems are limited to only two or three options of final gassed density, in a narrow energy range of RBS80 – RBS140. Solid sensitised ANE can deliver fixed energy and density profile but it does not offer flexibility to change density or energy, and usually only one or two energy options are available to the blast design and execution team.

Orica's 4D™ technology transforms the energy delivery system by offering an extended energy range from RBS 50 to 170 at increments of 10 per cent – a significant increase at both ends of the energy spectrum. Another critical difference from conventional gassed ANE systems is 4D™'s ability to counteract the effect of hydrostatic pressure on the energy profile. The 4D™ explosive delivery and gassing technology ensures consistent collars, and the ability to specify and vary the energy level throughout the column without the requirement for decking or multiple pass loading. 4D™ enables precise energy delivery at various points within the blasthole, or the blast in general, as required.

REAL WORLD APPLICATION

As of August 2024, the 4D™ bulk system has had extensive lab and field testing and has been deployed at three underground mining operations. The following examples show either final project data from these three mining operations or initial inferences, and the potential applications.

Stope blasting optimisation at Dugald River Mine

Background

The first implementation of the 4D™ bulk system globally occurred at MMG's Dugald River zinc mine in north-west Queensland, Australia. This implementation was as a multi-phase project between August 2022 and December 2023. While the initial stages of the project were purely focused on validating and verifying the system, the later Phases 3 and 4 set targets for blasting performance against an established baseline to measure the effectiveness of the extended energy range in improving blasting performance. This paper will review the performance of 4D™ in Phase 4 of the project between August and December 2023, using the largest data set, and the availability and deployment of the full range of 4D™ energy from RBS 50–170.

The Dugald River management team selected several Key Performance Indicators (KPIs) where adjusting energy was likely to lead to improvements. The metrics selected are listed below and are shown visually in **Error! Reference source not found.**. All the metrics were recorded as part of the mine's business as usual activities, meaning the project did not require any additional work to collect data, and for which a statistically relevant baseline could be easily produced. The KPIs were as follows:

- Stope recovery. The percentage of ore recovered from within the stope shape, up to a maximum recovery of 100 per cent. Typically, this is hardest to achieve along the footwall contact.
- Hanging wall dilution. Overbreak outside the planned stope shape leading to mining unwanted waste rock with ore.
- Brow failure rate. Stopes in which there was unwanted overbreak at the brow of the extraction level, past the first row of ground support, were deemed to have a failed brow.
- Cleanouts and redrills: The number of metres of redrills and hole cleanouts required in stopes where the same downholes were loaded and fired in more than one event, or lift.

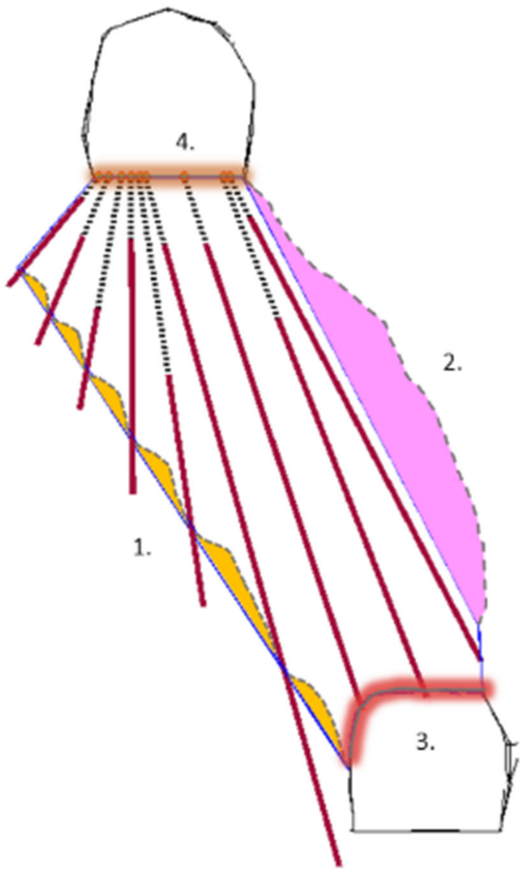


FIG 1 – Typical challenges faced in a Dugald River stope.

Baseline practice and performance

Conventionally, blast designers at Dugald River are restricted to choosing low, standard, or high-density ammonium nitrate emulsion (ANE). Changing the explosive energy within the ring is not simple. Hydrostatic pressure increases the density and energy at the toe of long columns and limits the maximum column length. Overall, the lack of energy control options for designers often leads to unfavourable blasting results. Typical stope recovery in comparable stopes was 90 per cent and typical dilution was 11 per cent.

The hanging wall contact between ore and waste is the main source of dilution at Dugald River. The stope geometry usually places a single parallel, longhole along this contact. To achieve the desired stope shape, it is necessary to consistently distribute just enough energy along the hanging wall to break the ore up to the point of contact and no further. Recovering all the ore on the footwall presents a different challenge. The ore is more confined and multiple holes intersect the contact at different angles, sometimes penetrating the barren host rock.

Brow failure is a common issue at the intersection with the extraction level. An existing improvement project was in progress, using a charge of approximately two metres of low density ANFO at the contact with the brow. Even with this method of reducing energy, brow failure rates were 44 per cent. Hole cleanouts and redrills were common in any situation where the toe of the blastholes was loaded and fired in the first firing event, and the remaining portion of the hole was to be fired in a subsequent event. Excess energy from the explosive column caused damage to the upper portion of the hole and access drive, and this often resulted in re-work to enable the subsequent loading of the holes.

4D™ solution

Using 4D™ to deploy a wide range of energy throughout the blast provided several different solutions for the problems described, without requiring any changes to drilling or other practices on-site. A joint workshop between MMG and Orica produced a 4D™ loading guideline document. A summary of the proposed loading for the different hole types, as well as conventional loading practices is shown in TABLE 1.

TABLE 1
Conventional and proposed 4D™ loading options by hole type

Hole type	Conventional loading	Proposed 4D™ loading
Hanging wall holes	Low density ANFO or 0.8 g/cc ANE	50–70 RBS
Brow holes	Low density ANFO (toe charge)	50–60 RBS (toe charge)
Winze holes	0.8 g/cc ANE	70–80 RBS
End wall holes	0.8 g/cc ANE	90 RBS
Easer holes	1.0 g/cc ANE	110–130 RBS
Footwall stabbing holes	1.0 g/cc ANE	150–170 RBS

An illustration of some of the proposed loading in practice within a stope ring is shown in FIG **2**.

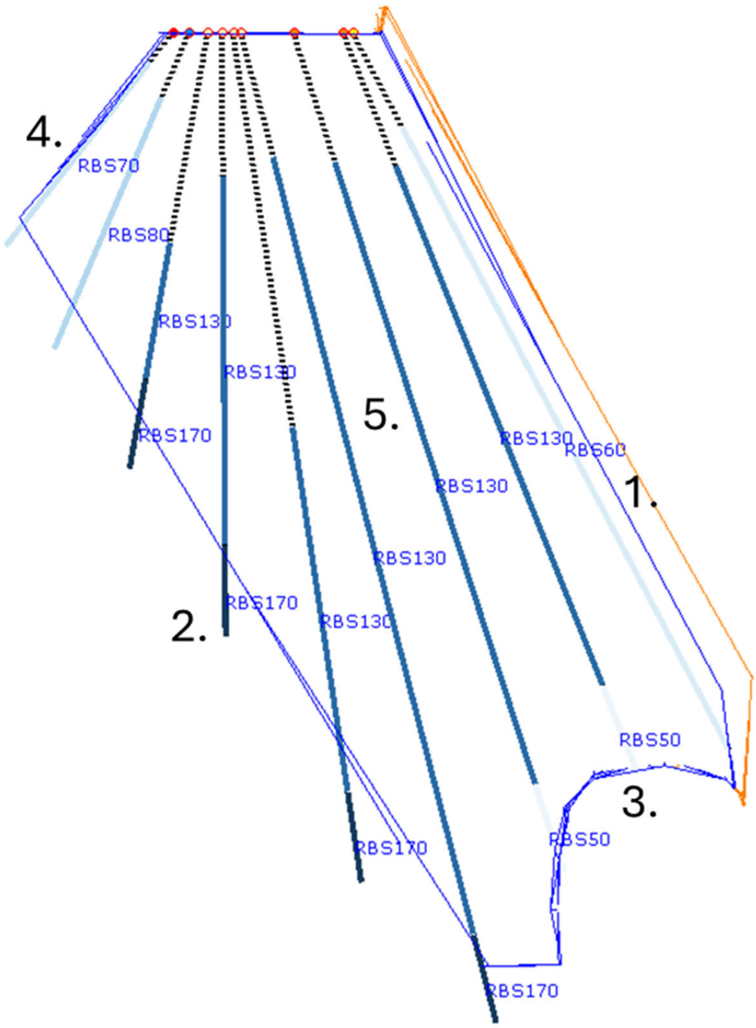


FIG 2 – Typical 4D™ loading in a Dugald River stope. Colour represents Relative Bulk Strength, as annotated.

Within the ring, the reasoning for each selection by application is as follows:

- Hanging wall holes used a consistent low energy charge of between RBS 50–70. Variance within this range was typically determined based on factors such as the drilled stand-off from the hanging wall, the existence of known faults or geological structures in the proximity of the hanging wall, and the performance of existing stopes within the same part of the mine. In narrow stopes, or stopes where the hanging wall was particularly susceptible to overbreak a lower energy charge was occasionally used in the next hole to function as an additional buffer.

- High energy toe charges were loaded in the holes stabbing the footwall where recovery was typically challenging to achieve. This ranged from RBS 150–170 depending on the orientation of the footwall, the length of the hole, the final toe spacing and burden on any given ring, and the amount of subdrill used. The energy reduces in that part of the hole in the middle of the stope. The ability to change energy quickly and easily at any point within a hole and load in a single pass gives the blast designer flexibility in making decisions about energy distribution.
- In the inverse of the high energy toe charge, holes drilled adjacent to the brow in the final ring used a low energy toe charge of RBS 50–60. This charge was typically 2–3 m in length and was intended to reduce the likelihood of unwanted damage and failure to the brow. The remainder of the hole was loaded with a higher energy charge, in this case RBS 130.
- A low energy charge, RBS 70, was also deployed in the stope shoulders, where maintaining the stope shape can sometimes be challenging. In this example the adjacent hole was also loaded with less energy, in this case RBS 80. While this location within the stope was not a major source of overbreak or dilution the ability to control it helped to further improve overall conformance to design.
- The bulk of the stope easers or production holes were loaded with RBS 130 in this example. This represents an increase in energy from the conventional 1.0 g/cc emulsion used on-site. This higher energy tended to improve fragmentation. The energy deployed within any given stope can be selected based on the requirements for the blast, but in most cases a charge of between RBS 90–130 was suitable for most easer holes within a stope.

Trial results

During the final phase of the trial, from August to December 2023 a total of 28 blasts across 23 stopes were loaded with the 4D™ system (most stopes consist of two or more blast events). The data regarding stope performance, brow control, and hole cleanouts was collected for these blasts as part of the mine's business as usual practices. A baseline data set of 24 similar stopes in the same mining areas that were loaded and fired within the same time frame as the 4D™ blasts was used to compare performance. The baseline and 4D™ data from the trial is presented in TABLE 1TABLE 2. By every measure, the 4D™ blast outcomes were better.

TABLE 2

Baseline and 4D™ performance at Dugald River mine.

KPI	Baseline performance	4D™ performance	Relative change
Hanging wall dilution	11.0%	3.7%	- 66%
Stope recovery	90%	93%	+ 3%
Brow failure rate	44%	12%	- 73%
Cleanout metres per stope	44.5 m	23.3 m	- 48%
Redrill metres per stope	5.4 m	5.1 m	- 6%

As each stope firing was a learning process, best practices were refined throughout the duration of the trial. The most appropriate energy levels for the hanging wall hole and footwall stabbing toe charges were identified by poor blast performances occurring when the energy levels for hanging wall holes exceeded RBS 70, and when footwall stabbing holes were loaded with RBS130, instead of the recommended RBS 150–170 range. After these blasts had been analysed and the loading parameters refined, performance was further improved. In stopes where loading followed the revised recommendations hanging wall dilution averaged 2.6 per cent, and stope recovery 94.9 per cent. The best performing stope during this phase recorded 1 per cent dilution and 99.3 per cent recovery.

There was also a significant improvement in brow failure rates, from a 44 per cent failure rate using conventional explosives to 12 per cent using the low energy 4D™ option. 4D™ eliminated the requirement to stock a speciality low density ANFO packaged product for this specific application, with a simplified magazine inventory, reduced freight requirements, and reduced manual handling. Hole re-drills were unaffected, with a very slight improvement observed, but hole cleanout requirements were approximately halved. This was attributed to the improved control of the final uncharged collar when using the 4D™ system. This represents a considerable time and cost saving through reduced re-work.

Conclusions

While the improvements in hanging wall dilution and stope recovery are positive in isolation, it is also important to consider them in relation to one another. In the baseline data set it was evident that while many stopes performed well in one or the other of these metrics they tended to perform poorly in the other. For example, the best performing 50 per cent of baseline stopes achieved a stope recovery of 95 per cent, but a hanging wall dilution performance of 8.5 per cent, while the top 50 per cent of 4D™ trial stopes recorded an average of 96.4 per cent recovery with only 2 per cent dilution. The top 50 per cent of baseline blasts in relation to hanging wall dilution achieved 2.7 per cent dilution, but only 93 per cent recovery, while the 4D™ performance was 1.3 per cent dilution at 94.6 per cent recovery. The ability to reliably achieve improved results in both metrics in the same stope represents a move towards optimising the drill and blast processes. This is visualised in FIG **3**, which shows a ranking of all baseline and 4D™ trial stopes by their stope recovery performance. The best performing stopes are on the right-hand side, and the worst performing stopes are on the left side. The respective hanging wall dilution results for the same stopes are also plotted. The absence of any large variations in hanging wall dilution, and consistently high stope recovery performance demonstrates the benefit of controlled energy distribution in critical parts of the blast.

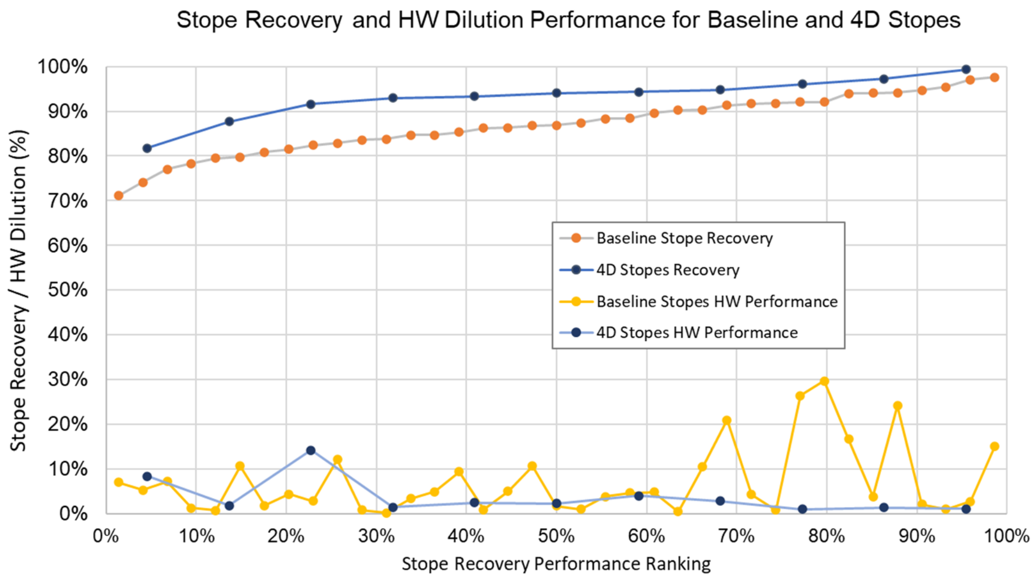


FIG 3 – Stope recovery and hanging wall dilution performance for baseline and 4D™ trial stopes.

The improvements in various performance metrics during the 4D™ system trial was significant. While a monetary value was not assigned to each of the metrics, for the two primary KPIs of hanging wall dilution and stope recovery, a joint value estimation was made by MMG and Orica. Scaling the improved stope recovery to a full year's mine production is equivalent to an uplift in Net Smelter Returns (NSR) of A$23.5 million, and the reduction in dilution was equivalent to a saving in load and haul costs of A$1.4 million. There was no monetary value assigned to cycle time efficiency improvements through improved conformance to stope shape, the reduction of the brow failure rates, and the reduction in hole cleanouts – but since all these metrics showed large improvements it is likely that there would be significant economic benefits in these areas.

It is acknowledged that bulk explosives are just one of many key factors that will affect drill and blast performance in underground mining. Technological improvements in other fields such as the ability to derive geological information from the drilling process, as well as accurately mapping the deviation of the as-drilled hole are now becoming more frequent and commercially available to underground mining operations. Combining this technology with the ability to select the optimum energy levels from an extended range will increase the ability of the drill and blast engineer to design a blast for a desired outcome, and for the operations personnel to achieve this result.

Development blasting applications

Background

Early-stage trials at a mine in North America during early 2024 focused on the capability of the 4D™ system in development mining. These trials provided valuable insights into the system's performance under real-world conditions, particularly in the challenging environments typical of development mining. The trials demonstrated the system's ability to deliver precise energy distribution, which is crucial for achieving optimal blast outcomes. The results showed that the 4D™ system can significantly enhance the efficiency and effectiveness of development mining operations, paving the way for broader adoption of this innovative technology.

Geology, drilling, and explosives have the greatest influence on blast performance. Geology is most influential because the rock type, structure, and condition directly affect how the blast will propagate and break the material. Understanding the geological conditions allows for better planning and execution of the blast. Drilling is the next most influential element, as precise drilling patterns and hole placements are crucial for achieving the desired blast outcome. Accurate drilling ensures that the energy from the explosives is distributed effectively throughout the rock mass. Finally, the choice and application of explosives are essential for optimising the energy release and achieving the desired fragmentation. While all three factors are interdependent, geology defines the underlying conditions, drilling defines the framework, and explosives deliver the energy within these two constraining factors.

Development blasting is especially challenging because there is no free face for relief. The correct application of energy in development mining is critical to ensure that the cut and blast pull to full depth across the entire face, particularly in the burn cut and shoulder holes. Proper energy distribution ensures that the perimeter does not experience overbreak or underbreak, which can lead to structural instability and increased operational costs. Excess energy can be just as problematic as insufficient energy. By precisely controlling the energy delivered to each blasthole, the 4D™ system helps to achieve a uniform blast profile by reducing damage to the surrounding rock mass. This precision not only enhances safety and efficiency but also contributes to the overall success of the mining operation by reducing waste and optimising resource recovery.

Conventional development practices in underground mining are often constrained by the limited options available for energy distribution. Typically, these practices rely on a few different energy bulk products, specialty packaged products, and strategic hole placement as the primary means of controlling energy. This approach can be restrictive, as it does not allow for the fine-tuning of energy levels needed to optimise blast performance. The inability to precisely control energy distribution can lead to suboptimal blast outcomes, such as uneven breakage, overbreak, or underbreak, which can compromise the efficiency and safety of the mining operation. Relying on a limited range of energy products can increase operational costs and reduce flexibility in responding to varying geological conditions.

An example of a blast design using conventional explosives, and the blasting outcomes from the blast is shown in FIG **4** (the example shown is not from the trial site but is indicative of typical issues facing development mining). This highlights typical issues that may be encountered in development mining: failure to achieve a full advance in the burn (1), hole butts indicating failure to achieve a full advance throughout the face (2), dishing at the extremities of the blast indicating the buffer row has failed to break to the perimeter (3), and a poor perimeter profile (4), with both excessive overbreak (5) and underbreak (6). A revised loading plan using 4D™ is shown in Figure 4, with the relative energy compared to the standard design shown. While detailed surveys have not yet been completed in development blasts using 4D™ initial performance appears to be significantly improving blasting performance.

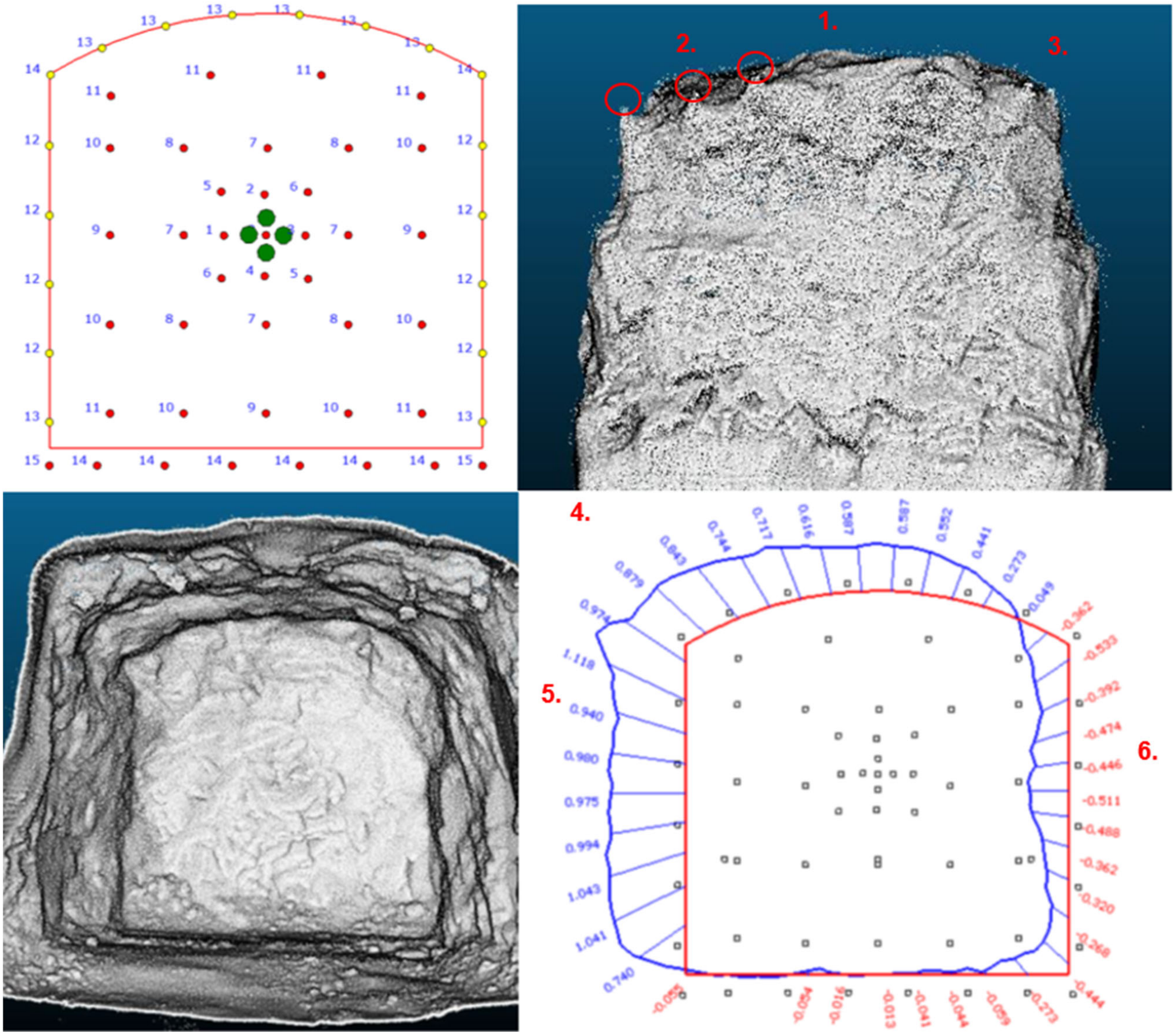


FIG 4 – From top left clockwise: a typical blast design for development heading, a plan view of the post blast 3D scan, a 2D slice from the heading scan showing overbreak and underbreak from profile, and a front on view of the 3D scan.

4D™ applications

4D™ enables improvements in development mining performance by applying many different energy levels throughout the blast. High energy can be allocated to highly confined parts of the blast, such as the lifters and corner holes, where it can be challenging to achieve a full advance with conventional explosive energy levels. In the burn cut where the holes are close together, reliable detonation under extreme conditions is essential to create the void for the box to break into, setting up success for the rest of the blast. Conversely, lower energy can be used in the perimeter holes to maintain the profile and prevent overbreak. This precise control over energy distribution enables more effective and efficient blasting, reducing waste and improving overall blast outcomes.

In addition to potential improvements in general blasting performance the ability to adjust energy as required will be useful in many other situations. In the event of blocked or missing holes, adjacent holes can be loaded with increased energy, or in the event of very weak rock mass conditions lower energy can be used in multiple rows of holes, besides just the perimeter holes. Additionally, it is possible to consider the potential to expand patterns – typically challenging given the small hole diameters used in development mining.

An example of the potential alternative distribution of energy is shown in TABLE 3 and visually represented in FIG **5**. This highlights the increased flexibility of a system for selective distribution of energy throughout a blast to achieve specific goals, without the requirement to source and carry speciality products. It is also possible for operators to adjust energy distribution at the face to consider hole conditions. The ability to tailor energy distribution is likely to lead to improved advance efficiency (blasted metres achieved relative to drilled metres) and perimeter performance.

TABLE 3

A comparison between typical conventional explosive selection and proposed 4D™ options, with relative energy difference highlighted.

Hole type	Typical conventional explosive selection	Estimated RBS	4D™ explosive selection	Change in RBS
Burn holes	1.0 g/cc ANE	100%	140 RBS	+40%
Easer holes	1.0 g/cc ANE	100%	110 RBS	+10%
Lifter holes	1.0 g/cc ANE	100%	140 RBS	+40%
Buffer holes	1.0 g/cc ANE	100%	80 RBS	-20%
Perimeter holes	0.8 g/cc ANE	67%	60 RBS	-11%

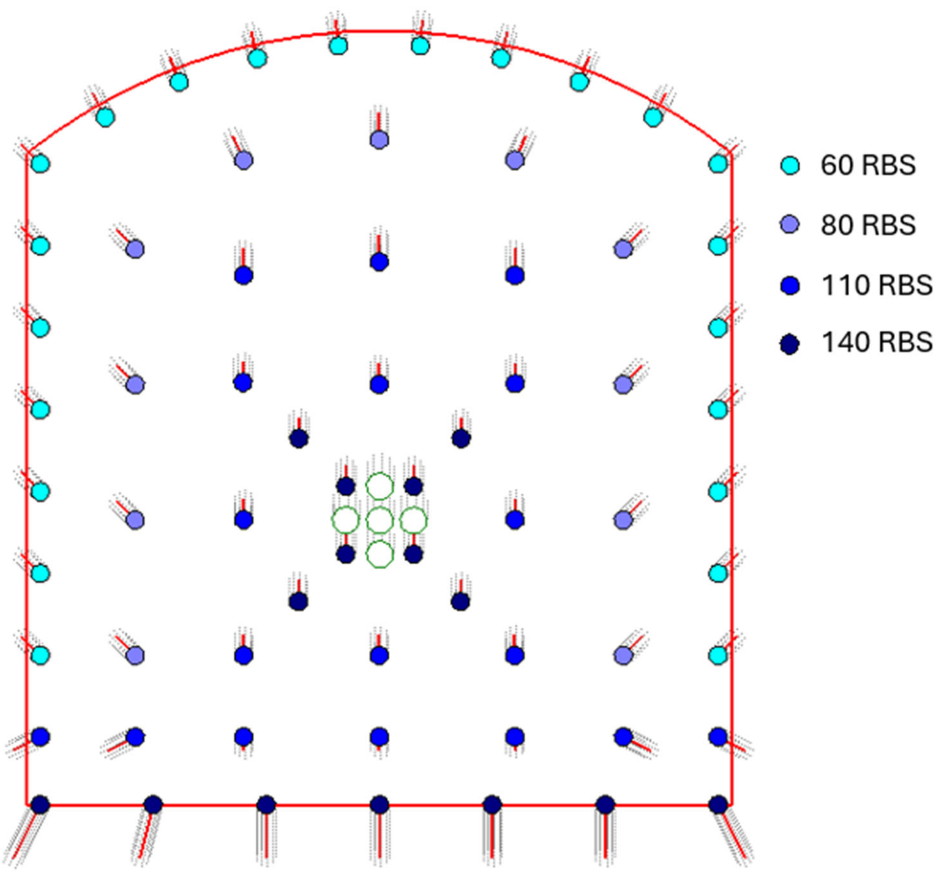


FIG 5 – Visual representation of proposed 4D™ energy distribution.

Energy applications in complex production environments

Early-stage trials of the system commenced at an underground copper mine in Chile in mid-2024. The applications at this operation target many of the same metrics as Dugald River, and using the experience from the Dugald River trial, particularly around multiple in-hole energies to achieve a variety of results from the same home.

Leveraging this prior experience, during this trial it is intended to explore the potential to increase the number of in-hole energies within the same hole to three or more. In particular there is a requirement for low energy at both the contact with the hanging wall, and close to the brow, while maintaining high energy for the bulk of the stope to ensure that fragmentation is kept below a critical level for downstream ore handling. Unlike the Dugald River mine example the contact with the hanging wall tends to be in the form of holes perpendicular to the contact, rather than parallel with it. This creates a challenging situation when loading with conventional explosives. It is intended to use the 4D™ system to deliver multiple energy options within the same hole. While this is similar in application to some of the work previously completed at Dugald River, the scale and complexity of the stope energy requirements will require multiple in-hole energies in a much wider variety of holes. An example of this is shown in FIG **6**, with the intended stope excavation shape shown by the green dashed line.

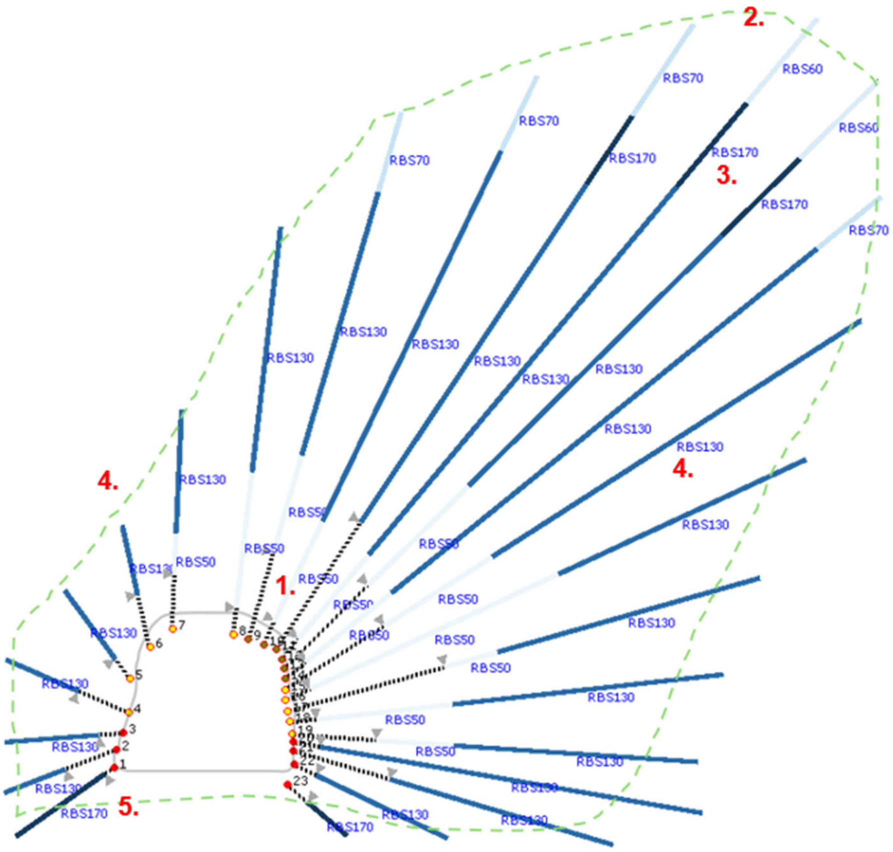


FIG 6 – Proposed loading of multiple energies in complex production environment, with the green dashed line showing the intended stope shape.

The key design decisions implemented here are as follows:

- Use of RBS 50 close to the brow, to maintain stability at the extraction level.
- Use of a low energy toe charge of RBS 60 and RBS 70 at the most critical part of the hanging wall contact.
- Use of a small high energy charge of RBS 170 towards the end of the longer holes, were spacing increases, and the need to maintain the required fragmentation demands a higher energy charge.
- Moderate to high energy levels (RBS 130) used along other intersections with the stope boundary, and within the bulk of the stopes.
- High energy (RBS 170) charges in two holes at the toe of the stope, to increase the ease of ore extraction.

CONCLUSIONS

While there has to date only been one large scale trial with the 4D™ system there have been many useful learnings that are now being applied to two other trial sites. Both trials are currently at initial stages and progressing with the work outlined above. However, it is evident from all three operations that this technology represents a major update to the capability of underground bulk explosive loading. It will function as an enabler for blast designers to target specific outcomes, and for operations personnel implementing blast designs to achieve the design and outcomes. It will enable modification to drill and blast practices.

Future technology integrations

The future of blasting envisioned by the authors includes an integrated design-for-outcome system. The system will combine data collected during drilling and mucking earlier blasts, combined with design and as-charged digital records, interpreted by design algorithms. The data will include rock strength and condition, water levels and the as-drilled hole track and collar position. The algorithm will adjust the density and mass of each charge within and between each hole based on a desired blast outcome. The system will manage constraints including vibration, geometry, and water.

Blastholes will be primed and charged autonomously with minimal human supervision. Wireless initiation and delivery system automation are enabling technologies essential to achieving this vision. Continuously variable energy within and between blastholes and decks will contribute to the adaptability of this system in production and development mining in upholes and downholes in all types of ground, and for all blasting scenarios. 4D™ brings this vision closer by providing an expanded range of charging options from a single delivery system, using one emulsion and gasser formulation.

ACKNOWLEDGEMENTS

Orica would like to acknowledge all of those who have worked on the development of the 4D™ system, and its deployment to sites across the globe. Orica would also like to acknowledge and thank the foundation customers at the sites on which these products have been trialled, in particular MMG who have given permission to publish data from the trial.

Digital mapping for rock mass discontinuities – opportunities and challenges

A Fereshtenejad[1], S Mehrishal[2], J Kim[3], J Leem[4] and J Song[5]

1. Geotechnical Engineer, GHD Pty Ltd, Melbourne Vic 3000. Email: sayedalireza.fereshtenejad@ghd.com
2. BK Assistant Professor, Department of Energy Resources Engineering, Seoul National University, Seoul, South Korea. Email: ahmad@snu.ac.kr
3. PhD Candidate, Department of Energy Resources Engineering, Seoul National University, Seoul, South Korea, Email: kjineon@snu.ac.kr
4. PhD Candidate, Department of Energy Resources Engineering, Seoul National University, Seoul, South Korea, Email: sooyalim@snu.ac.kr
5. Professor, Department of Energy Resources Engineering, Seoul National University, Seoul, South Korea. Email: songjj@snu.ac.kr

ABSTRACT

Rock mass discontinuity mapping plays a crucial role in developing a reliable Discrete Fracture Network (DFN), providing insights into the distribution of geometrical and mechanical properties of discontinuities. This enables an accurate assessment of geotechnical infrastructure and mining excavations. Data obtained through conventional mapping approaches are substantially limited by factors such as accessibility and subjectivity. Moreover, these conventional methods may pose inherent risks due to manual techniques, exposing practitioners to potential dangers. Recent digital developments in remote surveying techniques offer opportunities for safer and more reliable rock mass discontinuity surveys. These technologies allow extensive three-dimensional surveying and the production of high-resolution 3D surface models, applicable at any time. This paper presents a workflow for digital discontinuity mapping employing drone technology and photogrammetry. Additionally, the capabilities and challenges of applying artificial intelligence (AI) algorithms in the rock mass discontinuity characterisation process are discussed.

INTRODUCTION

Knowledge of faults and fractures within the orebody and surrounding rocks is essential in minimising safety risks in mining engineering. In subsurface studies, discontinuity data are commonly collected from outcrops where they are intersected. Traditionally, data collection involved engineering geologists using compass clinometers to measure discontinuity dip and dip direction. This was followed by manual recording on paper sheets, noting additional characteristics such as persistence, aperture, waviness, seepage, and infill materials. However, this method is limited in terms of accessibility, cost-effectiveness, and time efficiency due to its manual nature. It is also prone to bias and selective sampling, particularly when employed by less experienced practitioners.

In recent years, there has been a surge in digital advancements that have revolutionised traditional discontinuity data collection methods, data storage, and discontinuity analyses, eventually improving the safety and stability of mining and geotechnical projects. These advancements have significantly increased the reliability of discontinuity data mapped in the field and subsequently improved the accuracy of discontinuity analyses.

This paper introduces a comprehensive workflow for digital discontinuity mapping using drone technology and photogrammetry techniques and highlights the process of leveraging artificial intelligence (AI) algorithms for rock mass discontinuity characterisation. Moreover, the challenges and opportunities that arise from integrating these technologies in geotechnical assessments are addressed.

LIMITATIONS OF TRADITIONAL JOINT MAPPING METHODS

Rock mass characterisation using traditional methods (Figure 1) has always suffered from a relatively small number of recorded quantitative 3D geometric measurements (Jin *et al*, 2023). A field surveyor working with a traditional analogue/digital compass and paper/digital field notebook typically records tens of orientation measurements daily (Novakova and Pavlis, 2019). Hence, the total number of measurements is limited, and obtaining a sufficient number of repeat measurements to establish statistical uncertainty may not be feasible in practice. Even if surveyors bother to make tens of measurements of a single face, they will severely limit the number of outcrops they can document daily (Allmendinger, Siron and Scott, 2017). It is often more rewarding to spend time to collect a lot of data of a relatively low degree of accuracy at many localities, rather than to concentrate on obtaining a few data with an extremely high degree of accuracy (Ramsay, Huber and Lisle, 1983). However, without data accuracy, it becomes impossible to precisely evaluate the jointing characteristics of rock masses. Thus, the ideal case is to make many measurements with high accuracy and repeatability across the entire outcrop.

FIG 1 – Traditional joint mapping technique (Wong, Chan and Millis, 2019).

Moreover, traditional discontinuity characterisation systems and their respective evaluation indicators rely on simple geometrical relationships. These methods only collect joint information from one-dimensional or two-dimensional space and cannot comprehensively explain the joint occurrence in 3D space. In particular, the dispersion of objective geological conditions and subjective surveying factors significantly impact the characterisation results (Hao *et al*, 2023; Jin *et al*, 2023). Overall, the data provided by traditional manual rock discontinuity survey is insufficient, inaccurate and can vary depending on the surveyor, and the process is difficult (access difficulty), time-consuming, and sometimes dangerous (Priest and Hudson, 1976; Franklin, Maerz and Bennett, 1988; Ferrero *et al*, 2009; Kong, Wu and Saroglou, 2020; Mehrishal *et al*, 2024).

DIGITAL DEVELOPMENTS AND REMOTE SURVEYING TECHNIQUES

Remote surveying methods such as digital drone photogrammetry and LiDAR scanning have the capability to capture detailed 3D data of rock outcrops with high resolution. The application of these techniques in mining and geotechnical engineering has rapidly developed, particularly in areas such as slope stability analyses and landslide monitoring. When compared with traditional survey methods, these techniques offer the following advantages (Kong, Wu and Saroglou, 2020):

- 3D high-precision and real-time data acquisition.
- Time and cost efficiency for large-scale or time restricted projects.
- Contactless and safe investigation for inaccessible and hazardous areas.
- Permanent record of data which eliminates the need for additional site visits for supplementary information.
- Diverse data acquisition capabilities ranging from macro-scale (eg regional geological hazards survey) to micro-scale (eg joint roughness coefficient estimation).

These techniques have become firmly established for the mapping and quantitative characterisation of rock mass discontinuities (Figure 2). The subsequent sections will introduce a workflow for determining discontinuity orientation, persistence, and spacing using the recent advanced digital joint mapping techniques.

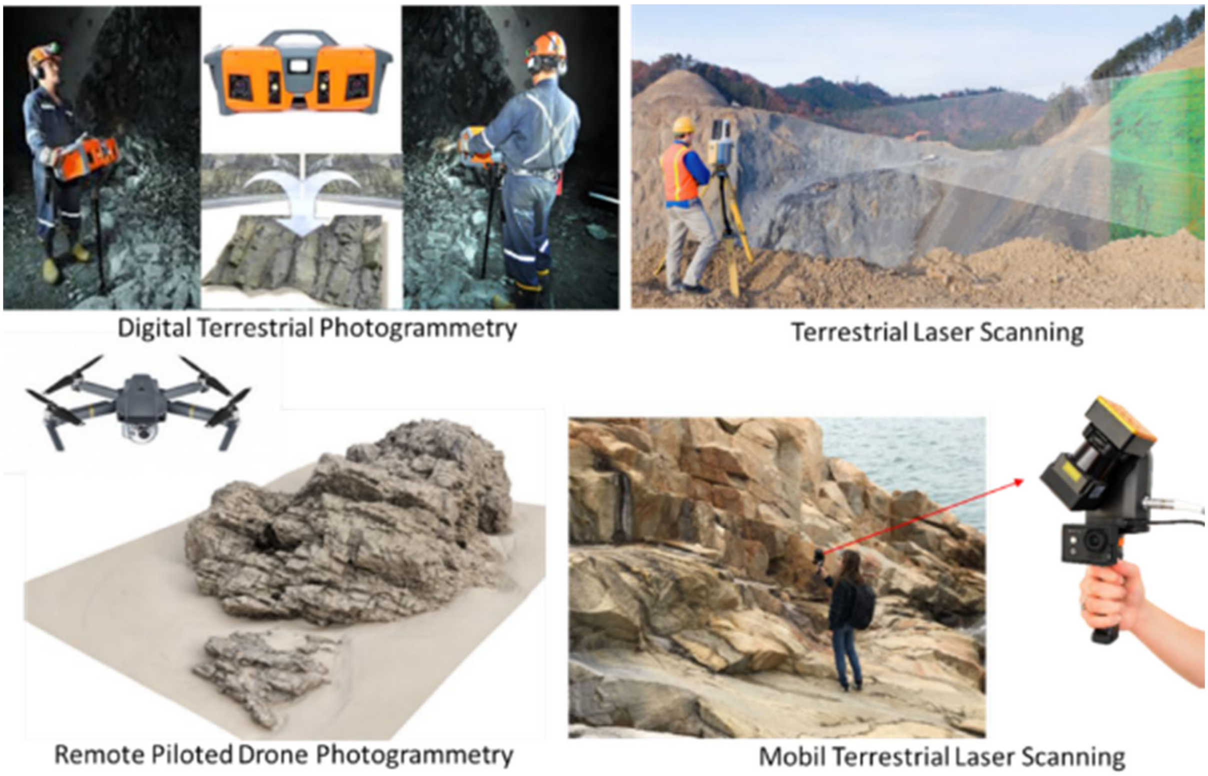


FIG 2 – Remote surveying techniques and digital joint mapping.

DIGITAL JOINT MAPPING – PRINCIPLES, OPPORTUNITIES AND CHALLENGES

Photogrammetry or laser scanning

Various remote surveying techniques are currently available for high-resolution 3D representation of rock surfaces, including terrestrial/aerial photogrammetry and LiDAR. LiDAR is categorised into four main systems in terms of deployment types: Terrestrial, Airborne, Unmanned, and Mobile LiDAR Scanning (TLS, ALS, ULS, and MLS) (Daghigh *et al*, 2022). These techniques have revolutionised geotechnical mapping, offering significant benefits over traditional methods. This section aims to compare the application of Laser Scanning and photogrammetry to rock mass characterisation, highlighting their advantages, limitations, and implications for discontinuity analyses. Figure 3 illustrates 3D models generated through photogrammetry and a lidar-based point cloud for an outcrop.

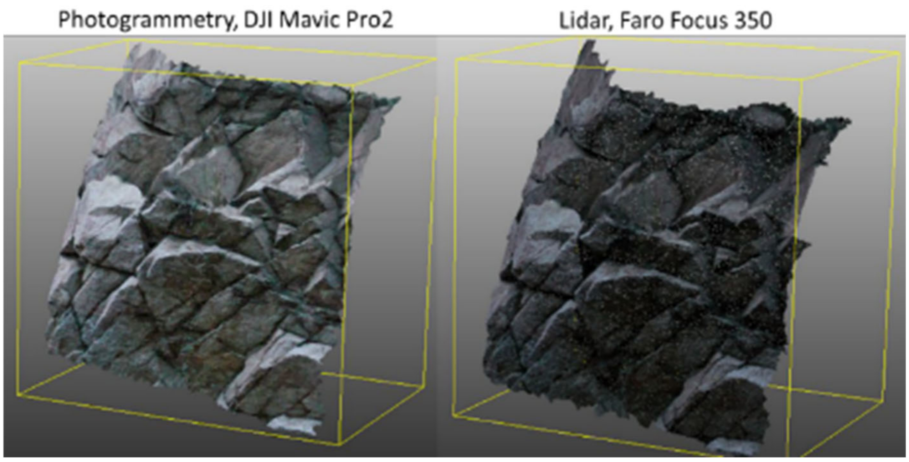


FIG 3 – 3D models generated through photogrammetry and a lidar-based point cloud for an outcrop under the same conditions.

The comparison between the applications of photogrammetry and laser scanning for rock mass characterisation is presented below, examining various perspectives.

Data Collection: Both methods offer substantial improvements in data collection efficiency compared to traditional methods. Laser scanning provides rapid data acquisition, mapping large areas in a short time frame, whereas photogrammetry enables comprehensive data collection through photography. However, laser scanning has a limited range of approximately 30 m, resulting in decreased data density with distance from the scanner (Wong, Chan and Millis, 2019). Conversely, photogrammetry boasts a theoretically limitless range but suffers from declining accuracy as the resolution of photos and the accuracy of control points decrease.

Post-Processing: Laser scanning typically requires less post-processing time, with point cloud generation taking less than an hour. In contrast, photogrammetry post-processing, particularly for high-resolution point clouds, can be time-intensive, often exceeding several hours. However, much of this time is user-free, minimising user effort.

Georeferencing: Georeferencing is essential for integrating survey data into a spatial context. Both methods require georeferencing against pre-existing survey data sets. However, real-time kinematic (RTK) photogrammetry more easily georeferences data with real-world coordinates, simplifying data processing. RTK positioning system is basically a GPS correction technique that provides a real time correction to the location data when the drone is capturing photos.

Cost Considerations: While these remote surveying techniques offer substantial benefits, their capital outlay is considerably higher than traditional methods. The ordinary package for laser scan (GEOSLAM ZEB HORIZON) and photogrammetry (Mavic 2 Enterprise Advanced), including hardware and processing software, can cost approximately A$100 000 and A$10 000, respectively. This higher initial investment must be weighed against the long-term benefits and efficiency gains provided by these technologies.

Reliability of Reconstructed Model: The reliability of a 3D reconstructed model is crucial for accurate rock mass characterisation. While both techniques produce detailed point cloud models ideal for recognising exposed planes, they encounter challenges in certain conditions. Photogrammetry struggles to capture data in low light situations, while laser scanning is limited to capturing RGB colour data required for joint trace mapping.

In conclusion, both laser scanning and photogrammetry offer significant advancements for joint mapping. However, photogrammetry emerges as the more suitable technique for rock mass characterisation (Figure 4). Photogrammetry's ability to create high-resolution 3D reconstructed models through comprehensive photography coupled with its theoretically limitless range, makes it particularly well-suited for capturing detailed data on rock outcrops and discontinuities. The use of RTK photogrammetry further streamlines georeferencing processes, simplifying data processing and enhancing overall efficiency. Additionally, photogrammetry's relatively lower cost for equipment and software makes it a more accessible option for individuals and organisations seeking to implement advanced remote surveying techniques for discontinuity analyses. Thus, for rock mass discontinuity characterisation, photogrammetry is the preferred choice due to its quality and reliability in data capture and analysis.

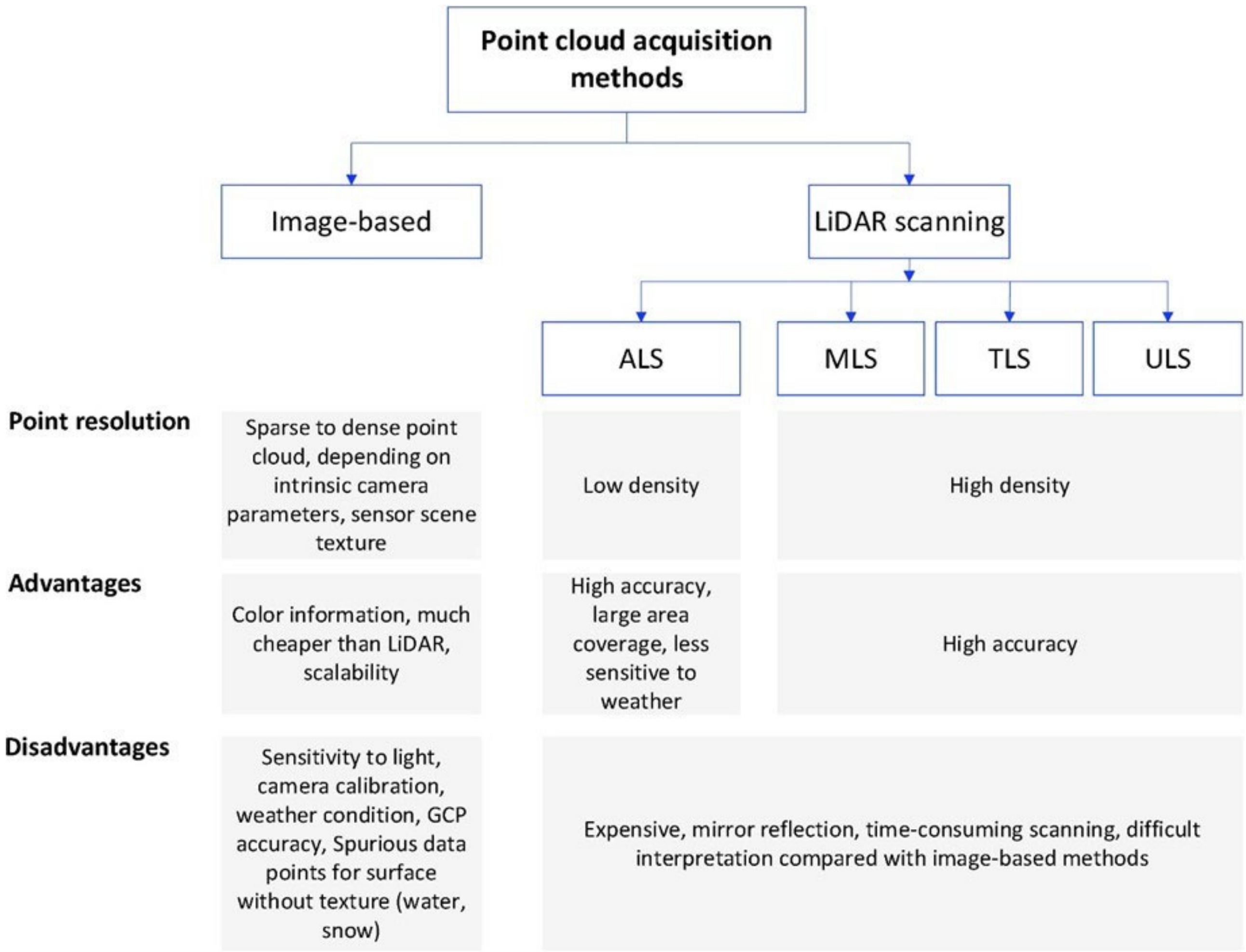


FIG 4 – Characteristics of image-based and LiDAR scanning point cloud acquisition methods (Daghigh *et al*, 2022).

Drone/camera selection

Recently, photogrammetry has been applied in characterising rock mass complexities across various scales, encompassing the measurement of small-scale joint roughness coefficients (JRC) to the calculation of large-scale failure volumes. However, sometimes, it lacks the accuracy and details required to capture the intricacies of small-scale features. In rock joint mapping, for instance, precise measurement of joint surface roughness is paramount. This section addresses the minimum requirements for implementing photogrammetric techniques specifically tailored for high-accuracy assessments, encompassing both small-scale and large-scale applications.

For accurately measuring JRC using photogrammetry, high image quality is crucial. The sensitivity of the JRC value to fine features of joint surfaces implies that even minor deteriorations in image quality can have a significant impact on both the resulting 3D model and its JRC evaluation (Dai, Feng and Hough, 2014; Kim *et al*, 2015). Blur (Sieberth, Wackrow and Chandler, 2014), noise (Eltner *et al*, 2016), and inadequate resolution (Aasen *et al*, 2015) are the primary factors that lead to a reduction in image quality and eventually a low-quality reconstructed model. In particular, when using drones, images are susceptible to motion blur caused by vibration. Therefore, it is recommended to utilise drones equipped with gimbals to mitigate and stabilise these vibrations (Smith, Carrivick and Quincey, 2016). For sharper imagery and to avoid out-of-focus blur, utilising cameras that permit smaller aperture settings (or larger F-numbers) is advantageous. While auto-focus features might mitigate out-of-focus blur, they can potentially modify camera calibration, adversely affecting Bundle Adjustment (BA) performance (Wenzel *et al*, 2013). Hence, it is recommended to use cameras that offer manual focus capabilities. Accurate JRC assessment demands a minimal Ground Sampling Distance (GSD), necessitating the use of high-resolution cameras. In general, cameras with longer focal lengths and larger sensor sizes are typically preferred. Compressing images into formats such as JPEG can result in the loss of high-frequency details required for conducting accurate JRC analysis. Consequently, storing images in the RAW format is strongly advised to preserve image quality and detail integrity.

Consumer-grade cameras are suitable for evaluating JRC in well-lit environments such as open pit mines (Micheletti, Chandler and Lane, 2015). However, in dimly lit areas such as underground tunnels or mines, the low lighting conditions increase the risk of noise in images. For these scenarios, it is preferable to use professional cameras with higher sensor efficiency. Furthermore, conditions with lower light require larger aperture settings (or smaller F-numbers) to achieve a high signal-to-noise ratio (SNR), demanding cameras that allow for aperture adjustments. The choice of pixel resolution is of great importance. Lower resolution can improve the SNR through pixel binning (Zhimin, Pain and Fossum, 1997), indicating a preference for cameras that allow for adjustment of pixel resolution. If such adjustment is not possible, the image resolution might need to be intentionally lowered during post-processing. To meet Ground Sample Distance (GSD) requirements, using a lower pixel resolution may require bringing the camera closer to the target. In such cases, drones equipped with range sensors are recommended to avoid potential collisions with the target.

Ground control points

Ground Control Points (GCPs) ensure accurate mapping and precise positioning of rock features in photogrammetry. GCPs establish a common reference frame, including true north and the vertical axis, which is critical for geological investigations, ensuring accurate orientation of discontinuity planes and revealing information about stress history and potential rockfall hazards. Knowing the true vertical axis, defined by GCPs, allows geologists to determine the dip direction of joints relative to gravity, aiding in identifying planes prone to failure and informing mitigation strategies for engineering projects. Therefore, a precise GCP placement facilitates the integration of generated 3D models into the geological workflow, enabling a more comprehensive understanding of rock mass behaviour.

Application of planar GCPs marked with an arrow sign is highly recommended in rock engineering projects. Leveling GCPs ensures that they are perfectly horizontal, establishing a well-defined reference frame for both true north and the vertical axis (Figure 5). Ideally, GCPs should be well-distributed throughout the survey area with known distances, easily identifiable in the imagery, and placed on stable terrain features. While precise GCP placement is crucial for accurate joint mapping, it can be labour-intensive and time-consuming. Therefore, using real-time kinematic (RTK) or post-processed kinematic (PPK) positioning methods is a recommended approach to minimise the number of GCPs needed.

FIG 5 – Placement of ground control points (GCPs) for accurate rock mass mapping.

RTK and PPK positioning systems are basically GPS correction techniques that provide a real time correction to the location data when the drone is capturing photos for drone photogrammetry projects. RTK utilises a real-time base station to transmit correction data to a rover, enabling centimetre-level accuracy. PPK involves collecting raw GPS data during drone flight and post-processing it later using data from a reference station, offering similar accuracy to RTK. The choice between RTK and PPK depends on factors like project budget, data processing capabilities, and the availability of a real-time base station.

Digital discontinuity characterisation

Rock discontinuities can be exposed as planes, edges, and joint traces on an outcrop. Figure 6 illustrates these elements using different colours: joint planes are represented using yellow, traces are highlighted in blue, and edges are shown using red polylines. Laser scanning has the advantage of directly acquiring 3D coordinates of exposed joint planes; however, it has limitations in distinguishing joint traces that exist on outcrop faces. Thus, studies on rock mass characterisation using laser scanning mostly focus on analysing joint orientation, roughness, and spacing through the detection of joint planes rather than joint traces (Feng *et al*, 2001; Feng and Röshoff, 2004; Slob *et al*, 2005; Gigli and Casagli, 2011; Han *et al*, 2017; Farmakis *et al*, 2020). Although some studies have been conducted to detect joint traces from laser scanning, they are mainly limited to joint traces caused by the intersection of joint planes (edges) or representative joint traces that are estimated from joint planes (Sturzenegger and Stead, 2009; Gigli and Casagli, 2011; Tuckey and Stead, 2016; Cacciari and Futai, 2016; Riquelme *et al*, 2018; Bolkas *et al*, 2018). Such techniques that only rely on 3D point cloud data face challenges in detecting joint traces on flat or weathered rounded rock surfaces.

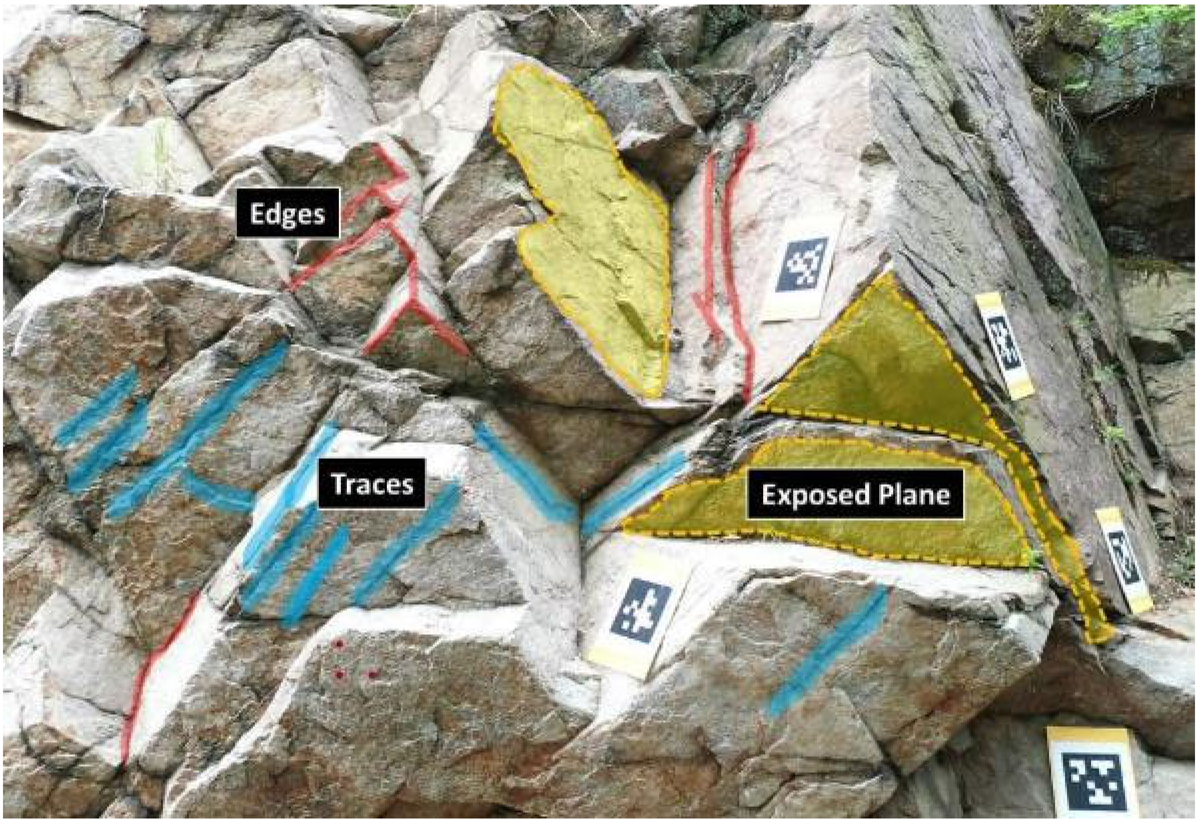


FIG 6 – Exposure of joints on a rock slope; exposed planes (highlighted in yellow), traces (highlighted in blue), and edges (indicated in red).

Point cloud-based joint characterisation

Most previous studies on remote surveying techniques mainly focus on detecting and characterising discontinuities by using 3D point cloud data analysis (Hagan, 1980; Zhang and Einstein, 2010; Zhang *et al*, 2018; Salvini *et al*, 2020; Chen *et al*, 2021a; Liu, Wronski and Danzl, 2021; Kong *et al*, 2021). The proposed approaches can be categorised into five groups: (a) Edge-based methods, (b) Region-growing methods, (c) Surface fitting methods, (d) clustering-based methods, and (e) Principal component analysis (PCA) methods (Daghigh *et al*, 2022). These techniques are known as segmentation techniques used to extract planar surfaces from point clouds.

CloudCompare and Discontinuity Set Extractor (DSE) are two popular open-source software tools used to extract exposed joint planes. CloudCompare is a general 3D data processing software that includes advanced features for analysing point clouds. While CloudCompare's existing functionality is helpful, it may not be sufficient for effectively extracting detailed plane surfaces from complex point clouds in rock formations. This limitation arises because the normal estimation feature in CloudCompare might not yield accurate results when applied to noisy point clouds with high curvature in rock formations. Daghigh *et al* (2022) thoroughly discusses some beneficial features of CloudCompare.

On the other hand, the DSE is a meticulous open-source tool specifically designed to detect and extract planar discontinuities from 3D point clouds (Riquelme *et al*, 2014). DSE implements a three-step process (Figure 7) for analysing a point cloud. First, it identifies planar regions by calculating local curvature using a k-nearest neighbour search and performing a coplanarity test. Second, it employs stereographic projection analysis to estimate the number of joint sets and their statistical parameters. Finally, it utilises a density-based spatial clustering of applications with noise (DBSCAN) clustering algorithm with consideration for point density variations to group points into relevant clusters. DSE is a semi-automatic approach that can handle noisy point cloud data. In complex rock outcrops, it may tend to yield over-segmented plane clustering. However, users can address this by disregarding insignificant clusters based on a minimum point threshold.

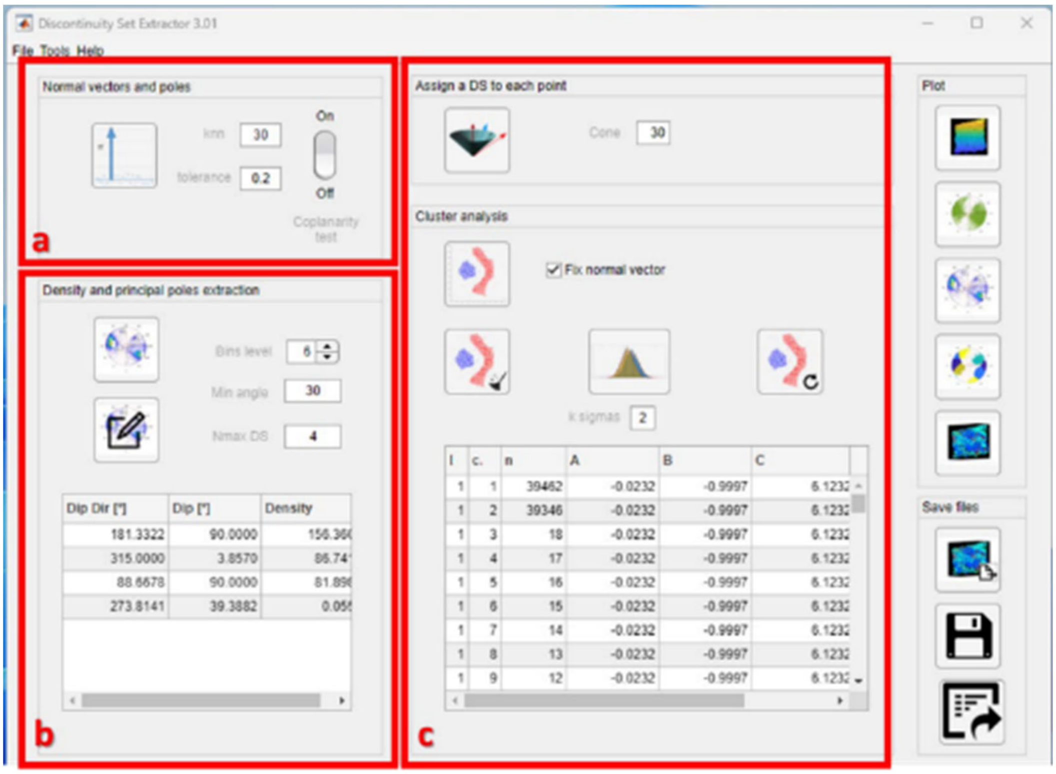


FIG 7 – DSE software for semi-automatic extraction of discontinuity sets from rock mass point clouds.

Textured 3D model-based joint characterisation

Discontinuities can manifest as either planar surfaces or embedded traces. Planar surfaces are flat and easily identifiable, whereas embedded traces are more challenging to detect. Traditionally, mapping joint traces involved conducting geotechnical field surveys using tape measures and geological compasses using scanline and window survey methods (Priest, 1993). However, recent advancements in non-contact methods have revolutionised the efficiency of *in situ* data collection for characterising geological and structural features of rock mass. Most photogrammetry studies have focused on joint trace detection, as this approach enables the generation of textured 3D models incorporating high-resolution RGB colour data.

To analyse joint traces on uneven rock surfaces the integration of images and point cloud data has been investigated (Deb *et al*, 2008; Umili, Ferrero and Einstein, 2013; Bolkas *et al*, 2018; Zhang *et al*, 2019; Guo *et al*, 2019; Lee *et al*, 2022a; Mehrishal *et al*, 2024). In detecting traces in digital images, distinguishing between edges and traces can be challenging due to shading, sudden texture changes, or colour variations caused by sharp topographic elevation differences. To overcome or at least reduce the effects of this problem, images can be taken at optimal conditions regarding shooting angle, image size or field of view, and camera distance. However, it is not always feasible to make these adjustments in the field due to various environmental limitations. Having a high-resolution textured 3D model of the outcrops, virtual digital image rendering can serve as an alternative to overcome practical field limitations. This method utilises the advantages of 3D modelling and image texture data, allowing us to virtually acquire an optimal digital image of the digital outcrop surface. This enables a semi-automatic detection of trace pixels on 3D textured mesh models, making the identification of these traces more accurate and reliable.

The orientation of rock discontinuities can be determined by analysing geometrical characteristics and spatial relations of traces in 3D space. In general, traces in rock mass can be divided into two groups: curved and straight. To identify curved traces, Mehrishal *et al* (2024) introduced a parameter (curvature index) for joint traces which indicates the accuracy in evaluating discontinuity planes from their traces. A curvature index greater than 5 per cent for a joint trace was found to be reliable to determine its discontinuity plane. There are various mathematical methods for fitting a plane to a detected curved trace in 3D space. One widely used approach is the principal component analysis (PCA) method. If the trace profile lacked sufficient longitudinal curvature to define the trace's plane (curvature index <5 per cent), the trace is considered as a straight line. Discontinuity planes can be also determined by identifying coplanar intersecting straight lines detected on adjacent outcrops. Since the discontinuity planes in rock mass are not completely planar and have undulations, spatial skew lines are considered to be co-planar when their Euclidean distance is smaller than a certain threshold value.

Mehrishal *et al* (2024) developed an algorithm that measures the orientation of discontinuities by extracting the 3D polylines of traces and analysing the traces in 3D space. They successfully demonstrated the synergistic potential of combining automatic joint trace detection techniques with the proposed trace network analysis algorithm to quickly and accurately identify discontinuity orientations within a rock mass. Figure 8 depicts the process and outcomes of the method applied, demonstrated through a case study conducted on a granitic outcrop.

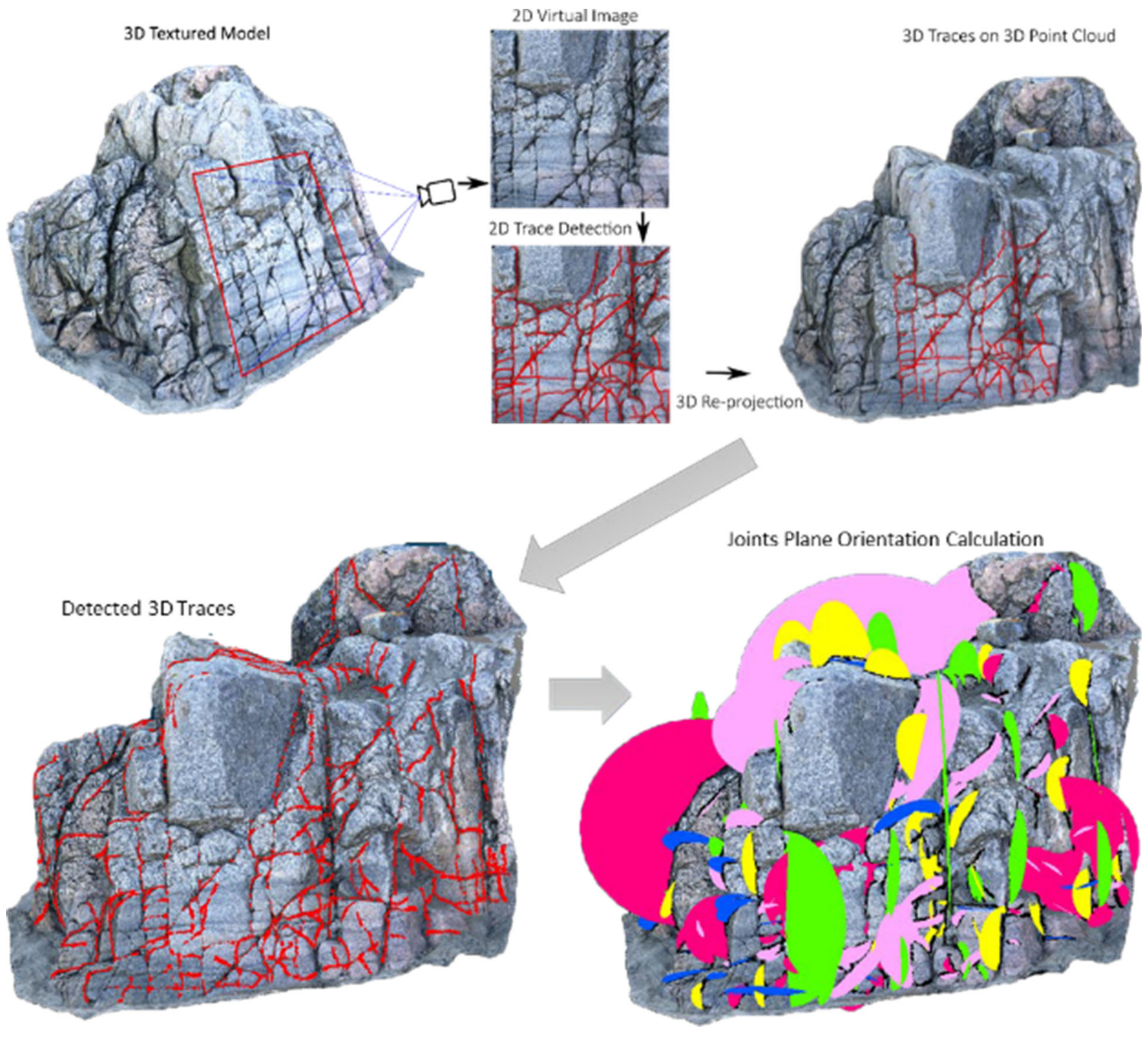


FIG 8 – Detection and analysing 3D trace networks for rock mass discontinuity orientation calculation.

Application of artificial intelligence to digital discontinuity characterisation

Image-processing techniques have been employed to identify joint trace pixels in digital images (Reid and Harrison, 2000; Kemeny and Post, 2003; Lemy and Hadjigeorgiou, 2003; Wang, 2005; Wang, Liao and Huang, 2007; Guo *et al*, 2012; Tang *et al*, 2021). However, these techniques are sensitive to factors such as rock textures, illumination conditions, and threshold settings. Furthermore, their performance can be significantly degraded by environmental factors such as shadows and bushes. To address these concerns, researchers have turned to deep-learning techniques, specifically convolutional neural networks, for joint trace detection due to their high performance in image recognition (Ronneberger, Fischer and Brox, 2015; Chen *et al*, 2021b; Lee *et al*, 2022b; Shi *et al*, 2023). While deep-learning-based classifiers have demonstrated high accuracy for flat rock surfaces (over 98 per cent accuracy versus human intelligence identification) (Shi *et al*, 2023), their effectiveness in detecting joint traces on uneven rock surfaces is limited. This limitation suggests that the ability of deep-learning techniques to accurately detect joint traces may be constrained in certain types of rock surfaces.

Mehrishal *et al* (2024) developed an updated data-structuring technique to overcome these limitations and improve the accuracy of joint trace detection from both 2D images and 3D rock surfaces. They compared their outcomes with results obtained from human evaluation to verify their proposed technique. In their study, the semi-automatic trace detection method proposed by Lee and Jeon (2022) was improved for measuring 3D traces polylines from 3D digital models. This improvement involved the utilisation of both digital image data and 3D point cloud data, and joint trace detection was performed using the deep-learning network DeepLabV3+ (Chen *et al*, 2021a). In addition, Mehrishal *et al* (2024) applied a 3D data-structuring technique to utilise pixel-wise data of joint traces detected by a trained classifier. In the 3D data-structuring process, point cloud data obtained using a commercial program were used. The data were structured through 2D thinning and segmentation, along with 3D projection, segmentation, and segment linking. Ultimately, linked segments were treated as 3D polylines, with each polyline in the output corresponding to a trace.

SUMMARY AND CONCLUSIONS

Accurate characterisation of rock mass discontinuities is of great importance for ensuring safety in mining operations and for evaluating the economic feasibility of mining projects. Traditionally, manual methods involving compass clinometers have been used, however they are limited in scope, accuracy, and efficiency. Recent digital advancements have transformed data collection and analysis, offering faster, more precise, and comprehensive techniques. Remote surveying methods like photogrammetry and LiDAR scanning provide high-resolution 3D data of rock outcrops and can be applied to overcome the limitations of traditional methods. Implementing these digital techniques involves selecting appropriate tools, such as laser scanning or photogrammetry, considering factors such as data collection efficiency, accuracy, and cost. Photogrammetry emerges as a preferred technique for capturing detailed data on rock outcrops due to its high-resolution 3D representations and cost-effectiveness. Ground control points ensure accurate mapping, while advanced algorithms and AI enable precise discontinuity characterisation using photogrammetry. Despite these advancements, challenges persist in detecting joint traces on uneven surfaces. Continued research and development in this field promise to further enhance the efficiency and accuracy of rock mass characterisation, leading to safer and more economically viable mining operations.

ACKNOWLEDGEMENTS

This work was supported by a grant from the Human Resources Development program (No. 20204010600250) by the Korea Institute of Energy Technology Evaluation and Planning (KETEP), funded by the Ministry of Trade, Industry, and Energy of the Korean Government (MOTIE).

The authors would like to thank GHD for providing the opportunity to publish this paper.

REFERENCES

Aasen, H, Burkart, A, Bolten, A and Bareth, G, 2015. Generating 3D hyperspectral information with lightweight UAV snapshot cameras for vegetation monitoring: From camera calibration to quality assurance, *ISPRS Journal of Photogrammetry and Remote Sensing*, 108:245–259. https://doi.org/10.1016/j.isprsjprs.2015.08.002

Allmendinger, R W, Siron, C R and Scott, C P, 2017. Structural data collection with mobile devices: Accuracy, redundancy and best practices, *Journal of Structural Geology*, 102:98–112. https://doi.org/10.1016/j.jsg.2017.07.011

Bolkas, D, Vazaios, I, Peidou, A and Vlachopoulos, N, 2018. Detection of Rock Discontinuity Traces Using Terrestrial LiDAR Data and Space-Frequency Transforms, *Geotechnical and Geological Engineering*, 36(3):1745–1765. https://doi.org/10.1007/s10706-017-0430-6

Cacciari, P P and Futai, M M, 2016. Mapping and characterization of rock discontinuities in a tunnel using 3D terrestrial laser scanning, *Bulletin of Engineering Geology and the Environment*, 75(1):223–237. https://doi.org/10.1007/s10064-015-0748-3

Chen, J, Huang, H, Zhou, M and Chaiyasarn, K, 2021a. Towards semi-automatic discontinuity characterization in rock tunnel faces using 3D point clouds, *Engineering Geology*, 291:106232. https://doi.org/10.1016/j.enggeo.2021.106232

Chen, J, Zhou, M, Huang, H, Zhang, D and Peng, Z, 2021b. Automated extraction and evaluation of fracture trace maps from rock tunnel face images via deep learning, *International Journal of Rock Mechanics and Mining Sciences*, 142:104745. https://doi.org/10.1016/j.ijrmms.2021.104745

Daghigh, H, Tannant, D D, Daghigh, V, Lichti, D D and Lindenbergh, R, 2022. A critical review of discontinuity plane extraction from 3D point cloud data of rock mass surfaces, *Computers and Geosciences*, 169:105241. https://doi.org/10.1016/j.cageo.2022.105241

Dai, F, Feng, Y and Hough, R, 2014. Photogrammetric error sources and impacts on modeling and surveying in construction engineering applications, *Visualization in Engineering*, 2(1):2. https://doi.org/10.1186/2213-7459-2-2

Deb, D, Hariharan, S, Rao, U M and Ryu, C-H, 2008. Automatic detection and analysis of discontinuity geometry of rock mass from digital images, *Comp Geosci*, 34(2):115–126. https://doi.org/10.1016/j.cageo.2007.03.007

Eltner, A, Kaiser, A, Castillo, C, Rock, G, Neugirg, F and Abellán, A, 2016. Image-based surface reconstruction in geomorphometry – merits, limits and developments, *Earth Surface Dynamics*, 4(2):359–389. https://doi.org/10.5194/esurf-4-359-2016

Farmakis, I, Marinos, V, Papathanassiou, G and Karantanellis, E, 2020. Automated 3D jointed rock mass structural analysis and characterization using LiDAR terrestrial laser scanner for rockfall susceptibility assessment: Perissa Area Case (Santorini), *Geotechnical and Geological Engineering*, 38(3):3007–3024. https://doi.org/10.1007/s10706-020-01203-x

Feng, Q H and Röshoff, K, 2004. In-situ mapping and documentation of rock faces using a full-coverage 3d laser scanning technique, *International Journal of Rock Mechanics and Mining Sciences*, 41:139–144. https://doi.org/10.1016/j.ijrmms.2004.03.032

Feng, Q, Sjögren, P, Stephansson, O and Jing, L, 2001. Measuring fracture orientation at exposed rock faces by using a non-reflector total station, *Engineering Geology*, 59(1–2):133–146. https://doi.org/10.1016/S0013-7952(00)00070-3

Ferrero, A M, Forlani, G, Roncella, R and Voyat, H I, 2009. Advanced geostructural survey methods applied to rock mass characterization, *Rock Mechanics and Rock Engineering*, 42(4):631–665. https://doi.org/10.1007/s00603-008-0010-4

Franklin, J A, Maerz, N H and Bennett, C P, 1988. Rock mass characterization using photoanalysis, *International Journal of Mining and Geological Engineering*, 6(2):97–112. https://doi.org/10.1007/BF00880801

Gigli, G and Casagli, N, 2011. Semi-automatic extraction of rock mass structural data from high resolution LIDAR point clouds, *International Journal of Rock Mechanics and Mining Sciences*, 48(2):187–198. https://doi.org/10.1016/j.ijrmms.2010.11.009

Guo, J, Liu, Y, Wu, L, Liu, S, Yang, T, Zhu, W and Zhang, Z, 2019. A geometry- and texture-based automatic discontinuity trace extraction method for rock mass point cloud, *International Journal of Rock Mechanics and Mining Sciences*, 124:104132. https://doi.org/10.1016/j.ijrmms.2019.104132

Guo, L, Liao, J, Zhong, F, Dong, K, Liu, X, Tao, J and Chen, J, 2012. A semi-automated methodology for rock mass discontinuity trace map construction, in *Proceedings of the 2012 International Conference on Image Analysis and Signal Processing*, pp 1–5. https://doi.org/10.1109/IASP.2012.6424980

Hagan, T O, 1980. A case for terrestrial photogrammetry in deep-mine rock structure studies, *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, 17(4):191–198. https://doi.org/10.1016/0148-9062(80)91085-2

Han, X, Yang, S, Zhou, F, Wang, J and Zhou, D, 2017. An Effective Approach for Rock Mass Discontinuity Extraction Based on Terrestrial LiDAR Scanning 3D Point Clouds, *IEEE Access*, 5:26734–26742. https://doi.org/10.1109/ACCESS.2017.2771201

Hao, J, Zhang, X, Wang, C, Wang, H and Wang, H, 2023. Application of UAV Digital Photogrammetry in Geological Investigation and Stability Evaluation of High-Steep Mine Rock Slope, *Drones*, 7(3):198. https://doi.org/10.3390/drones7030198

Jin, C, Liang, J, Cui, J and Wang, Q, 2023. Developing rock mass classification method using precise description of joints, *Environmental Earth Sciences*, 82(21):487. https://doi.org/10.1007/s12665-023-11184-8

Kemeny, J and Post, R, 2003. Estimating three-dimensional rock discontinuity orientation from digital images of fracture traces, *Computers and Geosciences*, 29(1):65–77. https://doi.org/10.1016/S0098-3004(02)00106-1

Kim, D H, Poropat, G V, Gratchev, I and Balasubramaniam, A, 2015. Improvement of photogrammetric JRC data distributions based on parabolic error models, *International Journal of Rock Mechanics and Mining Sciences*, 80:19–30. https://doi.org/10.1016/j.ijrmms.2015.09.007

Kong, D, Saroglou, C, Wu, F, Sha, P and Li, B, 2021. Development and application of UAV-SfM photogrammetry for quantitative characterization of rock mass discontinuities, *International Journal of Rock Mechanics and Mining Sciences*, 141:104729. https://doi.org/10.1016/j.ijrmms.2021.104729

Kong, D, Wu, F and Saroglou, C, 2020. Automatic identification and characterization of discontinuities in rock masses from 3D point clouds, *Engineering Geology*, 265:105442. https://doi.org/10.1016/j.enggeo.2019.105442

Lee, S and Jeon, S, 2022. Estimating Rock Mass Joint Roughness Using Terrestrial Laser Scanner and Artificial Neural Network, *All Days*, ARMA-2022-0662. https://doi.org/10.56952/ARMA-2022-0662

Lee, Y-K, Kim, J, Choi, C-S and Song, J-J, 2022a. Semi-automatic calculation of joint trace length from digital images based on deep learning and data structuring techniques, *International Journal of Rock Mechanics and Mining Sciences*, 149:104981. https://doi.org/10.1016/j.ijrmms.2021.104981

Lee, Y-K, Kim, J, Choi, C-S and Song, J-J, 2022b. Semi-automatic calculation of joint trace length from digital images based on deep learning and data structuring techniques, *International Journal of Rock Mechanics and Mining Sciences*, 149:104981. https://doi.org/10.1016/j.ijrmms.2021.104981

Lemy, F and Hadjigeorgiou, J, 2003. Discontinuity trace map construction using photographs of rock exposures, *International Journal of Rock Mechanics and Mining Sciences*, 40(6):903–917. https://doi.org/10.1016/S1365-1609(03)00069-8

Liu, Q, Wronski, L and Danzl, P, 2021. Processing outcrop point clouds to 3D rock structure using open source software, *IOP Conference Series: Earth and Environmental Science*, 833(1):012054. https://doi.org/10.1088/1755-1315/833/1/012054

Mehrishal, S, Kim, J, Song, J-J and Sainoki, A, 2024. A semi-automatic approach for joint orientation recognition using 3D trace network analysis, *Engineering Geology*, 332:107462. https://doi.org/10.1016/j.enggeo.2024.107462

Micheletti, N, Chandler, J H and Lane, S N, 2015. Investigating the geomorphological potential of freely available and accessible structure-from-motion photogrammetry using a smartphone, *Earth Surface Processes and Landforms*, 40(4):473–486. https://doi.org/10.1002/esp.3648

Novakova, L and Pavlis, T L, 2019. Modern Methods in Structural Geology of Twenty-first Century: Digital Mapping and Digital Devices for the Field Geology, in *Teaching Methodologies in Structural Geology and Tectonics* (ed: S Mukherjee), pp 43–54 (Springer: Singapore). https://doi.org/10.1007/978-981-13-2781-0_3

Priest, S D and Hudson, J A, 1976. Discontinuity spacings in rock, *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, 13(5):135–148. https://doi.org/10.1016/0148-9062(76)90818-4

Priest, S D, 1993. *Discontinuity Analysis for Rock Engineering* (Springer: Netherlands). https://doi.org/10.1007/978-94-011-1498-1

Ramsay, G, Huber, M and Lisle, R, 1983. *The Techniques of Modern Structural Geology* (Elsevier Science).

Reid, T R and Harrison, J P, 2000. A semi-automated methodology for discontinuity trace detection in digital images of rock mass exposures, *International Journal of Rock Mechanics and Mining Sciences*, 37(7):1073–1089. https://doi.org/10.1016/S1365-1609(00)00041-1

Riquelme, A J, Abellán, A, Tomás, R and Jaboyedoff, M, 2014. A new approach for semi-automatic rock mass joints recognition from 3D point clouds, *Computers and Geosciences*, 68:38–52. https://doi.org/10.1016/j.cageo.2014.03.014

Riquelme, A, Tomás, R, Cano, M, Pastor, J L and Abellán, A, 2018. Automatic Mapping of Discontinuity Persistence on Rock Masses Using 3D Point Clouds, *Rock Mechanics and Rock Engineering*, 51(10):3005–3028. https://doi.org/10.1007/s00603-018-1519-9

Ronneberger, O, Fischer, P and Brox, T, 2015. U-Net: Convolutional Networks for Biomedical Image Segmentation, in *Medical Image Computing and Computer-Assisted Intervention – MICCAI 2015* (eds: N Navab, J Hornegger, W M Wells and A F Frangi), 9351:234–241 (Springer International Publishing). https://doi.org/10.1007/978-3-319-24574-4_28

Salvini, R, Vanneschi, C, Coggan, J S and Mastrorocco, G, 2020. Evaluation of the Use of UAV Photogrammetry for Rock Discontinuity Roughness Characterization, *Rock Mechanics and Rock Engineering*, 53(8):3699–3720. https://doi.org/10.1007/s00603-020-02130-2

Shi, Y, Ballesio, M, Johansen, K, Trentman, D, Huang, Y, McCabe, M F, Bruhn, R and Schuster, G, 2023. Semi-universal geo-crack detection by machine learning, *Frontiers in Earth Science*, 11:1073211. https://doi.org/10.3389/feart.2023.1073211

Sieberth, T, Wackrow, R and Chandler, J H, 2014. Motion blur disturbs – the influence of motion-blurred images in photogrammetry, *The Photogrammetric Record*, 29(148):434–453. https://doi.org/10.1111/phor.12082

Slob, S, Van Knapen, B, Hack, R, Turner, K and Kemeny, J, 2005. Method for Automated Discontinuity Analysis of Rock Slopes with Three-Dimensional Laser Scanning, *Transportation Research Record: Journal of the Transportation Research Board*, 1913(1):187–194. https://doi.org/10.1177/0361198105191300118

Smith, M W, Carrivick, J L and Quincey, D J, 2016. Structure from motion photogrammetry in physical geography, *Progress in Physical Geography: Earth and Environment*, 40(2):247–275. https://doi.org/10.1177/0309133315615805

Sturzenegger, M and Stead, D, 2009. Close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts, *Engineering Geology*, 106(3–4):163–182. https://doi.org/10.1016/j.enggeo.2009.03.004

Tang, Y, He, L, Lu, W, Huang, X, Wei, H and Xiao, H, 2021. A novel approach for fracture skeleton extraction from rock surface images, *International Journal of Rock Mechanics and Mining* Sciences, 142:104732. https://doi.org/10.1016/j.ijrmms.2021.104732

Tuckey, Z and Stead, D, 2016. Improvements to field and remote sensing methods for mapping discontinuity persistence and intact rock bridges in rock slopes, *Engineering Geology*, 208:136–153. https://doi.org/10.1016/j.enggeo.2016.05.001

Umili, G, Ferrero, A and Einstein, H H, 2013. A new method for automatic discontinuity traces sampling on rock mass 3D model, *Computers and Geosciences*, 51:182–192. https://doi.org/10.1016/j.cageo.2012.07.026

Wang, W, 2005. An Edge Based Segmentation Algorithm for Rock Fracture Tracing, in *Proceedings of the International Conference on Computer Graphics, Imaging and Visualization (CGIV'05)*, pp 43–48. https://doi.org/10.1109/CGIV.2005.16

Wang, W, Liao, H and Huang, Y, 2007. Rock fracture tracing based on image processing and SVM, in *Proceedings of the Third International Conference on Natural Computation (ICNC 2007)*, pp 632–635. https://doi.org/10.1109/ICNC.2007.643

Wenzel, K, Rothermel, M, Fritsch, D and Haala, N, 2013. Image acquisition and model selection for multi-view stereo, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-5/W1:251–258. https://doi.org/10.5194/isprsarchives-XL-5-W1-251-2013

Wong, D, Chan, K and Millis, S, 2019. Digital Mapping of Discontinuities, Transformation in Geotechnical Engineering – Technology, Digital and Innovation.

Zhang, L and Einstein, H H, 2010. The Planar Shape of Rock Joints, *Rock Mechanics and Rock Engineering*, 43(1):55–68. https://doi.org/10.1007/s00603-009-0054-0

Zhang, P, Li, J, Yang, X and Zhu, H, 2018. Semi-automatic extraction of rock discontinuities from point clouds using the ISODATA clustering algorithm and deviation from mean elevation, *International Journal of Rock Mechanics and Mining Sciences*, 110:76–87. https://doi.org/10.1016/j.ijrmms.2018.07.009

Zhang, P, Zhao, Q, Tannant, D D, Ji, T and Zhu, H, 2019. 3D mapping of discontinuity traces using fusion of point cloud and image data, *Bulletin of Engineering Geology and the Environment*, 78(4):2789–2801. https://doi.org/10.1007/s10064-018-1280-z

Zhimin, Z, Pain, B and Fossum, E R, 1997. Frame-transfer CMOS active pixel sensor with pixel binning, *IEEE Transactions on Electron Devices*, 44(10):1764–1768. https://doi.org/10.1109/16.628834

Tactical medical mining rescue – closing the gap of professional medical attention in environments with difficult accessibility

A Fichtner[1], F Reuter[2], C Staak[3] and H Mischo[4]

1. Professor, Zeisigwaldkliniken Bethanien Chemnitz, Technische Universität (TU) Bergakademie Freiberg, TU Dresden, Medizinische Fakultät; 09130 Chemnitz, Germany. Email: andreas@drfichtner.info
2. Technische Universität (TU) Bergakademie Freiberg, 09599 Freiberg, Germany. Email: frank.reuter@lfb.tu-freiberg.de
3. Universitätsklinikum Halle, 06120 Halle (Saale), Germany. Email: christine.staak@yahoo.de
4. Professor, Technische Universität (TU) Bergakademie Freiberg, 09599 Freiberg, Germany. Email: helmut.mischo@mabb.tu-freiberg.de

ABSTRACT

In mining and remote areas of resource industry, there has been a development towards lacking emergency medical first aid response, that creates a potential disadvantage for patients after work accidents and other medical emergencies compared to standard population. This raises the question how a professional emergency medical coverage can be provided underground, taking into account lacking medical professionals in small resource companies combined with long rescue times. Aiming on the closure of this gap, a team of the mine rescue brigade from the Research and Training Mine Reiche Zeche (Forschungs-und Lehrbergwerk (FLB) Reiche Zeche) of the TUBAF Technische Universität Bergakademie Freiberg in Freiberg/Germany and its cooperating emergency departments of the Freiberg District Hospital and the Zeisigwaldkliniken Bethanien Chemnitz developed a totally new rescue concept using elements from tactical medicine and advanced emergency medicine combined with a specifically designed compact equipment and a highly standardised teaching curriculum. A fully new standardised and condensed tactical medical approach was developed including specifically adjusted equipment, and was taught in a didactically optimised way within 16 lessons in two days. Objective Structured Practical Examinations (OSPE) using manikins and simulated patients were conducted and compared to the identical exam of the reference group, which consisted of advanced paramedics. The standardised tactical medical scheme includes vital functions and body checks, advanced life support, nasal and intraosseous drug application, supraglottic airway management, artificial ventilation, thoracocentesis, bleeding control including tourniquet, fracture repositioning and splinting, transport bedding and thermal preservation. The developed Tactical Medical Mining Rescue (TMR) concept was subsequently included in the German guidelines for mine rescue services in 2022 and is already implemented in many companies in Germany and several international projects.

INTRODUCTION

In many regions of the world, an undersupply has been observed in the medical first aid emergency response to mining- and resource industry accidents compared to work accidents in urban environments. This results in a potential disadvantage for work accident patients and raises the question of how a professional emergency medical coverage can be provided, taking into account the given lack of medical professionals in small resource companies as well as the problem of generally long rescue times.

Tactical medicine in general encompasses a special field of mainly pre-hospital care that requires patient care principles to be adapted to the given circumstances (Neitzel and Ladehof, 2023). These are usually characterised by a particularly dangerous situation which can place an extraordinary physical and psychological burden on the helpers and require special training and equipment appropriate to the mission. Various constellations, such as a severe limitation of personnel and material resources, a confusing operating environment and prolonged rescue times, complicate and delay professional care in medical emergencies. Injuries in these environments are often serious and life-threatening and therefore medical emergencies. Tactical medicine is primarily associated with military and police operations as well as disasters and major incidents where, in contrast to civil emergency medicine, medical care must be integrated into the context of military or police task fulfilment. However, operational situations requiring a tactically orientated approach can also arise in the civilian sector from everyday activities such as leisure and sport (eg skiing, climbing, speleology) and at the workplace in special branches of industry (eg offshore, mining, forestry).

Such emergency situations usually have two decisive factors in common:

1. The lack of rapid availability of medical resources (personnel, equipment) in areas that are difficult to reach in impassable terrain.
2. Special dangers at the scene (such as rescue from great heights and depths, non-breathable atmosphere, risk of collapse) which require local and specialised knowledge for rescuers (SRHT – special rescue from heights and depths, self-contained breathing protection), special physical fitness and special technical equipment.

This makes it almost impossible and unreasonable for emergency paramedics and emergency physicians without special training and equipment to rescue and provide first aid to patients in a pre-hospital setting.

Due to the special operational rescue concepts in mining, mine rescue teams are often the only rescue services available that have the specific knowledge of the site and are therefore best suited to the special underground conditions. In order to close the addressed gaps in medical care, a group of specialists with emergency medical and technical expertise as well as medical didactics competence has developed a standardised and validated training curriculum including condensed treatment algorithm and specialised miniaturised medical equipment for mine rescue teams, intended for the advanced rescue of miners from underground accidents (Reuter *et al,* 2022; Reuter and Fichtner, 2021).

The two main problems – the lack of medical resources and the need for specialised local and technical knowledge of the area of operation – are addressed by training mine rescue teams in extended emergency medical rescue. These specially trained miners then have the emergency expertise to carry out medical measures at an advanced level that is otherwise reserved for emergency doctors or paramedics. The current availability of extremely user-friendly medical products as well as equipment and training specially configured for such operations enable mine rescue teams to safely carry out the absolutely essential and time-critical medical measures within a narrow, strictly algorithm-based framework, even without in-depth medical knowledge.

Tactical Medical Mining Rescue (TMR®) is a unique course for rescue in tactical situations by medical laymen. After initial scepticism about teaching invasive emergency medical measures to laypersons, even the medical community now is increasingly convinced by the need of finding new ways of bridging the otherwise very long intervals until handover to public emergency rescue. In the meantime, the solutions for tactical medical emergency care proposed by TMR® have also been met with high interest from neighbouring aid organisations, for example in the extended training of first responders in sparsely populated areas and mountain rescue teams. At the same time, the concept is also gaining importance internationally for the emergency care of injured workers in large industrial projects in remote regions beyond mining.

SPECIAL BOUNDARY CONDITIONS IN THE MINING INDUSTRY

In the early hours of 10 March 1906, a violent detonation shook the Courrières mine in France. The explosion and toxic fumes killed 1099 miners (Farrenkopf and Rothmund, 2010). This disaster emphasises the particular danger posed by toxic gases in the mining industry. Thus, already more than 100 years ago, conclusions were drawn regarding the tactics for rescuing injured miners and strategies were developed that were adapted to the special characteristics of mining: The training, organisation and supervision of the mine rescue services was given its own structure. Training in the use of breathing apparatus and, as an example, emergency respirators specially developed for mining (Oxylator FR300B) have become an indispensable cornerstone of the training of mine rescue teams (Deutscher Ausschuss für das Grubenrettungswesen, 2022).

The limits of civil emergency medicine provided by the public rescue service above ground for use in mining are limited by many further factors, such as the lack of long-term respiratory protection, bulky medical equipment that is unsuitable for hazardous areas and long-transport distances underground, the lack of suitable means of communication or existing regulations of public rescue services for self-protection in hazardous areas. The significantly longer rescue times compared to the civilian sector regularly lead to the required response times being exceeded, depending on regional legislation (eg around 15 mins in Germany). In contrast, patients in mining operations in central Germany in 2018 and 2019, were usually only handed over to the civilian rescue service after one to two hrs at the earliest, and after 11 hrs at the latest (Reuter *et al,* 2023). Additionally, a recent survey of a large international mining company recorded at least one serious occupational accident every two days with a relevant sick leave of several days (data anonymised). Extended basic medical care by specially trained rescue workers until handover to the public emergency services could minimise injury-related complications and thus might significantly improve the medical treatment outcome.

The specific underground features were also considered in the relevant legislation: As an example, in Germany, mining law defines that the mining companies must independently organise their entire rescue operations (ABBergV, 2024). The public rescue services and the fire brigade are not permitted, at least not in their professional capacities, to carry out any underground rescue. Additionally, within the mining companies, it has been observed that the previously required level of qualification of company first aiders was no longer sufficient to ensure adequate emergency care on-site. Due to the severity of injuries to be expected, this is especially true when compared to the level of emergency care that could be provided by public rescue services.

TMR® CONCEPT – TRAINING, LEGAL FRAMEWORK, CERTIFICATION

With the TMR® rescue concept, medical lay rescuers in mining operations are now being provided with a medical action algorithm based on schemes that have been established in emergency medicine for years and have been combined to form a treatment algorithm that is both efficient and safety-optimised. This algorithm consists of a chain of practical skills in a narrow framework, and are set-up as a logical dichotomous decision tree, thus enabling the layperson to provide adequate initial medical care without professional medical qualifications.

A two-day standardised qualification course, using advanced tools of medical didactics, was developed and validated using a professional paramedic reference group to define the necessary competence levels. The modified c-AVPU-ABC2DE treatment algorithm is shown in Figure 1. As a logical therapy chain, it includes all elements for the initial assessment, emergency care and transport preparation of the injured person:

- Initial assessment of the patient and recognition of a vital threat.
- Resuscitation including defibrillation with AED (in the event of cardiac arrest, care is provided at ALS level).
- Securing the airway with LMA Supreme™ and semi-automatic ventilation (Oxylator FR 300B, Panomed).
- Circulatory stabilisation with colloidal volume replacement solution.
- Pain therapy via nasal or intraosseous administration of medication, depending on the patient's level of consciousness.
- Advanced haemostasis measures.
- Reduction and splinting of fractures.
- Detection and decompression of a Tension Pneumothorax.
- Active heating for body temperature maintenance.
- Transport positioning with fixed equipment.
- Ability to perform drag and vertical rescues, also under artificial ventilation.

Graduates of this structured and standardised training can typically provide complete medical treatment and get an injured person immobilised and ready for transport within 15 mins using the stream-lined treatment algorithm they have learned and the specially adapted equipment.

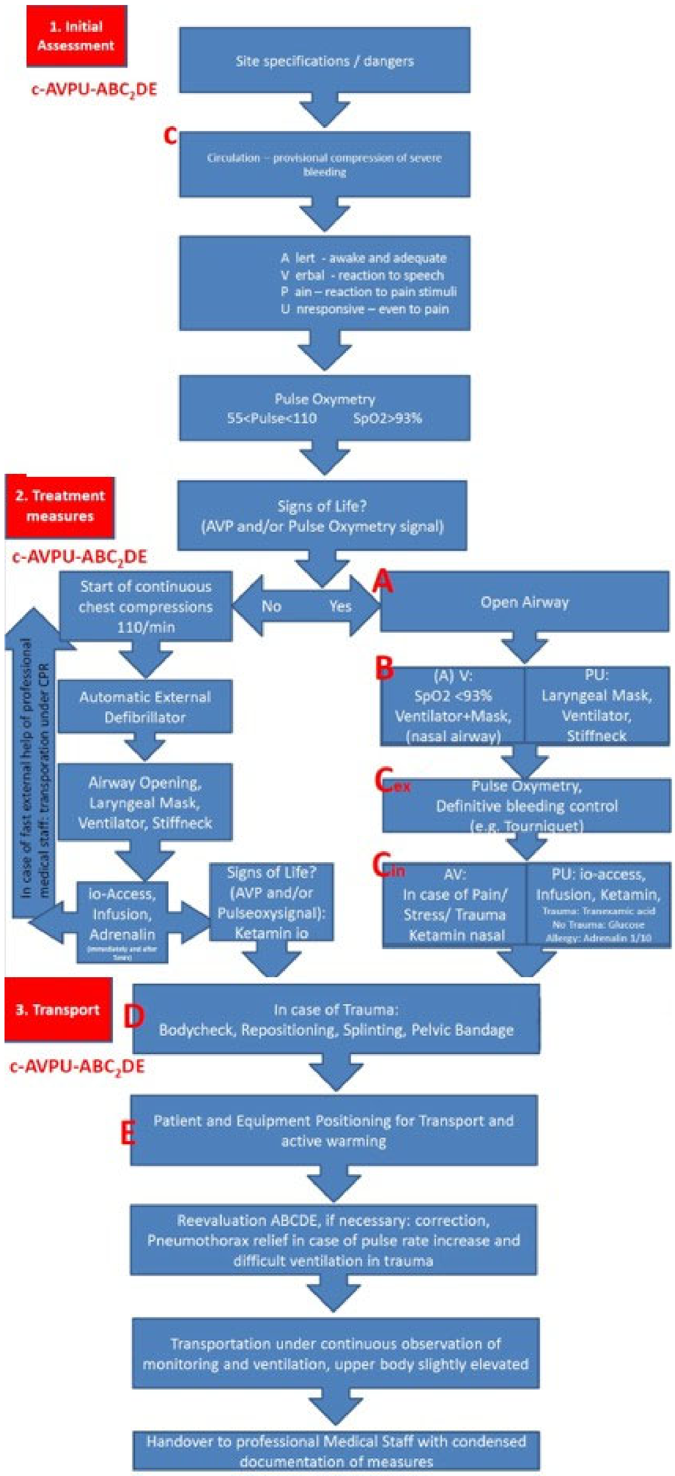


FIG 1 – Summary of the TMR® deployment scheme at a glance. This scheme, with additional detailed information, is part of the TMR® equipment and serves as a valuable aid during the operation (source: A Fichtner and F Reuter).

The specific condensed treatment algorithm is taught and emergency medical decision-making skills are learnt along with practical skills and invasive measures during the two-day training curriculum in a realistic operational environment. After the step-by-step standardised teaching according to the Peyton scheme using a simulation model, the participants go through several realistic accident scenarios with mock patients (Figure 2).

FIG 2 – Treatment according to TMR® concept (scenario with simulated patient) (photos: A Fichtner and F Reuter).

To demonstrate the skills learnt and to maintain the quality of the course, participants complete a final examination at seven stations, which is carried out as an 'Objective Structured Practical Examination'. The course validation shows that the mine rescue team can achieve statistically equivalent results in the narrowly defined area of training content in comparison to randomly selected rescue personnel with different levels of training (emergency paramedics and paramedics with two or three years of education).

In several tests, the mine rescue teams could even achieve better results than the paramedic subgroup of the lowest certification level (assistant paramedics). Figure 3 shows a comparison of the examination results of a mine rescue team and of the reference groups of public rescue services (emergency paramedics and paramedics only). When the OSPE examination was conducted again after a six-months practice-free interval, it was shown that the medical skills learnt could still be applied without any statistically verifiable loss of competence.

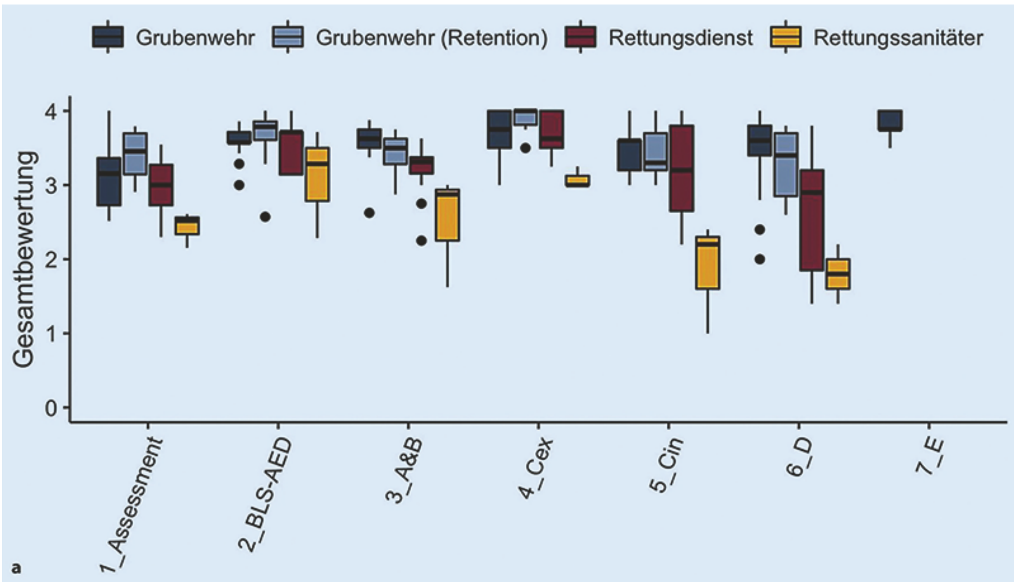


FIG 3 – Validation results of the TMR® course compared to the public ambulance service (Reuter *et al*, 2022) (source: A Fichtner and B Brunner).

The results underline the fact that the transfer of emergency measures, including invasive ones, to laypersons in a narrowly defined indication area after appropriate training and within the framework of a justifiable emergency situation is certainly possible while maintaining patient safety and is even necessary to bridge the therapy-free interval. In the meantime, the TMR® short concept has been firmly implemented in the training of mine rescue teams: Since June 2022, the federal German mine rescue regulations have required 'validated, extended training in first aid designed for underground and mining-specific conditions' (Deutscher Ausschuss für das Grubenrettungswesen, 2022), with the TUBAF serving as the certification and validation body. Refresher courses are organised every two years to maintain the level of competence.

The field training revealed an impressively high level of quality among the participants in terms of the structured processing of the TMR® deployment scheme and the associated treatment decisions. In addition to the correct indication of medical measures and their correct implementation, elements such as communication, team leadership, re-evaluation of the treatment process and reaction to the dynamics of the patient's condition are qualitatively assessed by the instructors. Two years after completing the TMR® course, these resulted in very good to excellent performances of the mine rescue teams. The results were often even better, with optimised teamwork and safety in the invasive measures to be carried out in just yearly minor repetitions, compared to the final scenarios of the TMR® basic training.

Of course, the medical responsibility of the lay rescuer ends as soon as specialised medical personnel is available. For the handover, all diagnostic findings and executed medical treatment so far have been recorded on a laminated information card (Figure 4), that will be attached to the patient for continuation of treatment by the specialised medical personnel of public rescue.

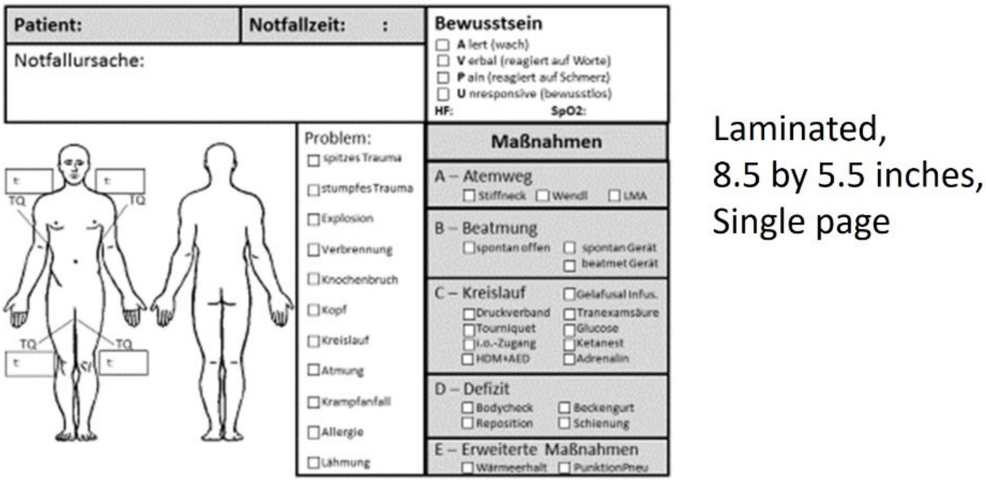


FIG 4 – Laminated patient diagnostic and treatment record (source: A Fichtner and F Reuter).

SPECIALISED MEDICAL EQUIPMENT

The standard medical equipment of public rescue services can only be used to a limited extent or not at all underground and in difficult-to-access surface locations. For the emergency rescue concept presented here, special equipment was therefore put together that can be stowed in a single compact, dirt and water-repellent rescue backpack, measuring only 47 cm in length (Figure 5). When selecting the equipment, the top priorities were user-friendliness and patient safety, a high success rate and practicality in a harsh operating environment. Fast and precise access to the circulatory system is of crucial importance in trauma rescue. Based on military tactics, an intraosseous system that is manually inserted into the sternum (EZ-IO® T.A.L.O.N.™ Needle Set) was selected for the TMR® concept. The set is equipped with a sternal positioning aid to avoid uncertainties in the application in case of extremity injuries and anatomical peculiarities can be avoided.

In order to prevent any overloading of the rescuers with too sophisticated medical background knowledge and to avoid application errors, the drug dosage forms were selected in a way that the medication from an entire ampoule is administered to an adult, thus eliminating the need for time-consuming dosage calculations. An LMA Supreme™ is used to secure the airway, which has advantages in terms of rapid insertion times with high success and low leakage rates (Russo *et al,* 2012). For emergency ventilation, the Oxylator FR 300B is used, which is a pressure-controlled semi-automatic ventilator that works independently of ambient air and is therefore applicable in toxic atmospheres. Thanks to the automatic pressure/flow system, the device automatically optimises the respiratory minute volume – no adjustments are necessary (StGB, 2024). A specially developed electrically operated warming mat (AK MedTec GmbH) was integrated into the transport system to maintain body heat especially in situations with impaired coagulation due to bleeding.

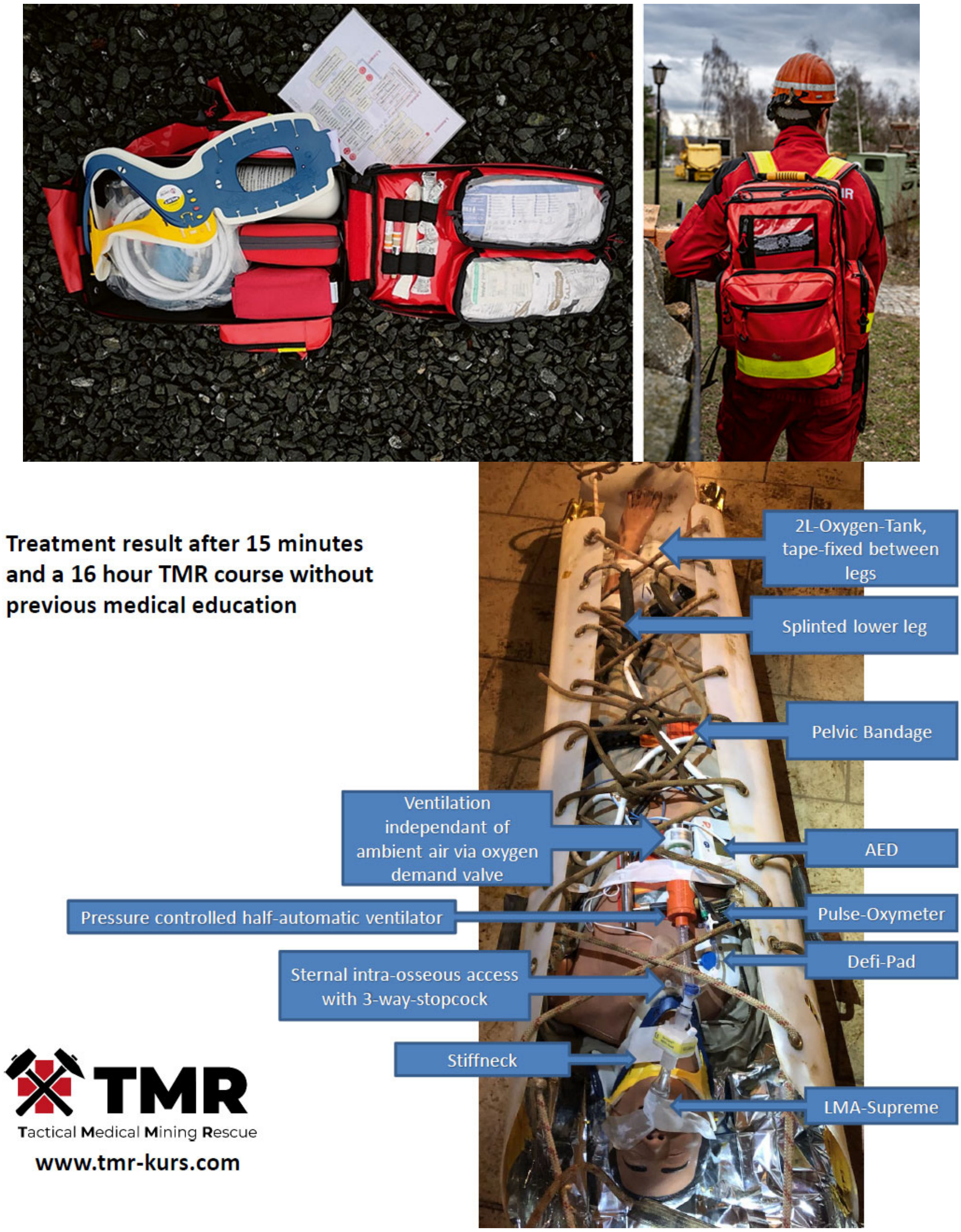


FIG 5 – Backpack (47 cm long) with included treatment scheme and equipment completely stowed except for the environment-specific stretcher (photos: D Müller and F Reuter).

CONCLUSIONS

The implementation of the TMR® concept in the mining industry within Germany was able to show – already at a real patient – that the gap of coverage by professional public emergency rescue services in difficult to access, hazardous areas can be closed by the strictly algorithm-based qualifications of non-professional rescue workers. The developers believe that these findings are also transferable to the emergency rescue of life-threateningly ill or injured patients in other industrial application or in remote regions to bridge the treatment-free interval until the arrival of or handover to the public rescue services. Hence, such on-top-qualified organised volunteer first aiders could help to efficiently close such gaps in care across the board, particularly against the backdrop of demographic and current political developments through further training with the TMR® concept.

The TMR® concept is currently also being introduced among raw material companies in Austria. Other countries, eg in regions of southern Africa, with often extended rescue times in the public rescue services, have also already expressed interest in the TMR® concept.

ACKNOWLEDGEMENTS

Special thanks for the opportunity to carry out the research and development work presented in this paper go to TUBAF Technische Universität Bergakademie Freiberg, Kreiskrankenhaus Freiberg gGmbH and Zeisigwaldkliniken Bethanien Chemnitz gGmbH.

REFERENCES

ABBergV, 2024. Bergverordnung für alle bergbaulichen Bereiche (Allgemeine Bundesbergverordnung). Available from: <www.gesetze-im-internet.de/abbergv/BJNR146600995.html> [Accessed: 4 April 2024].

Deutscher Ausschuss für das Grubenrettungswesen, 2022. Leitlinien des Deutschen Ausschusses für das Grubenrettungswesen für Organisation, Ausstattung und Einsatz von Grubenwehren. Available from: <https://deutsche-grubenrettung.de/wp-content/uploads/2022/07/Leitlinien-Grubenrettungswesen-Stand-2022.pdf> [Accessed: 4 April 2024].

Farrenkopf, M and Rothmund, S, 2010. Zugepackt – heißt hier das Bergmannswort: Die Geschichte der Hauptstelle für das Grubenrettungswesen im Ruhrbergbau, Dt, Bergbau-Museum, Bochum.

Neitzel, C and Ladehof, K, 2023. *Taktische Medizin: Notfallmedizin und Einsatzmedizin* (Springer: Berlin).

Reuter, F and Fichtner, A, 2021. Medizinisch-taktische Rettung im Grubenrettungswesen, *Taktik + Medizin,* 4:213–217.

Reuter, F, Fichtner, A, Brunner, B, Preuss, D, Herrmann, B and Herrmann, M, 2022. Entwicklung und Validierung eines Kurskonzepts zur medizinisch-taktischen Rettung unter Tage, *Med Klin Intensivmed Notfmed*, 117:531–541. https://doi.org/10.1007/s00063-021-00861-w

Russo, S G, Cremer, S, Galli, T, Eich, C, Bräuer, A, Crozier, T A, Bauer, M and Strack, M, 2012. Randomized Comparison of the I-Gel™, the LMA Supreme™ and the Laryngeal Tube Suction-D using Clinical and Fibreoptic Assessments in Elective Patients, *BMC Anesthesiol,* 12:18. https://doi.org/10.1186/1471-2253-12-18

Strafgesetzbuch (StGB), 2024. § 34 Rechtfertigender Notstand. Available from: <www.gesetze-im-internet.de/stgb/__34.html> [Accessed: 4 April 2024].

Application of multi-sensor and AI-based core logging for a reduction of decision-making time within mineral exploration field projects

C Garcia[1], I Luna-Berbesi[2] and A Krishnan[3]

1. Principal Geologist, DMT, Essen NRW 45307, Germany. Email: carlos.garciapina@dmt-group.com
2. Project Geologist, DMT Consulting Engineers, Toowong Qld 4066. Email: ivanricardo.lunaberbesi@dmt-group.com
3. Project Geologist, DMT, Essen NRW 45307, Germany. Email: aditya.krishnan@dmt-group.com

ABSTRACT

The discovery and exploration of deposits are progressively shifting to extremely remote regions and greater depths. As a result, exploration costs and the economic risk of a bad investment increase. Current megatrends in the exploration and mining sector indicate a growing demand for the implementation of automation, digitalisation, and machine learning techniques. The implementation of a multi-sensor-based core logging device (DMT, 2024) was done on 400 m of drill cores to optimise interdisciplinary processes in terms of time and quality, by using interlinked and consistent data in real-time, to obtain reliable predictions that support and speed up decision-making. The results are consistent with the laboratory data previously obtained by the mining company, highlighting the benefits of introducing ANCORELOG into their core logging procedures.

INTRODUCTION

Significant amounts of drill core are recovered from the early stages of exploration through the productive mining stage of a deposit. Lithological, mineralogical, geotechnical, structural, and geochemical drill core properties must be logged by geologists in a timely manner. Large quantities of drill cores are systematically sampled, and their chemical and mineralogical composition is examined in accredited laboratories. Based on the logging and laboratory results, further exploration procedures, evaluation of deposits, as well as the extraction and processing technology, are planned. In addition to the logistical challenges associated with sample transport, significant laboratory costs and often weeks of sample processing time can potentially lead to delays and long downtimes. Sensor-based, on-site drill core analysis in combination with real-time data processing can provide a remedy.

ANCORELOG is a multi-sensor equipped device that obtains continuous geochemical, mineralogical, and structural information from drill cores. ANCORELOG has been successfully implemented for different target elements and ores such as iron (Bauer *et al*, 2021), bauxite (Orberger *et al*, 2021), and copper (Bauer *et al*, 2022). The use of analytical methods, such as X-ray fluorescence (XRF), hyperspectral imaging (VNIR and SWIR), Raman spectroscopy, and image segmentation, based on high-resolution RGB images, are combined with machine learning techniques to provide a comprehensive classification of the deposit-based criteria such as lithology, alteration zones or structural domains.

METHODOLOGY

More than 400 m of drill cores from a copper mine were continuously scanned with ANCORELOG sensors (Figure 1), including:

- RGB high-resolution camera with a pixel size of 25 µm (40 pixels per millimetre).
- Hyperspectral camera (HSI) in the SWIR range (900 nm – 2500 nm), used to determine the mineralogical composition of rocks. Each pixel (250 nm) has a spectrum that is compared with those of the MICA library (mineralogical spectrum library) to assign a mineral category to each.
- The XRF sensor (Teixeira Mendes, 2021) was used continuously on the rocks and data were compiled every 20 cm. The resulting spectrum provides qualitative information (counts per second, cps) of the elements with atomic numbers greater than 15, specifically copper, iron, arsenic, and zinc for this project. Calibration to achieve elemental quantification of the XRF

sensor was performed by comparing the acquired spectra with the laboratory values provided by the company.

- Raman spectroscopy (Havisto *et al*, 2021) is an analytical method that detects the energy shifts of photons emitted from a monochromatic excitation source, in this case, a pulsed picosecond laser with a range of 532 nm, caused by an interaction mainly with molecular vibrations in the measurement sample. By detecting the characteristic energy shifts of molecules, typical Raman shift fingerprints allow the mineralogical composition of the sample to be determined. As a point-type measurement, the Raman sensor was only used in areas of interest, eg determining the composition of a vein or mineralisation.

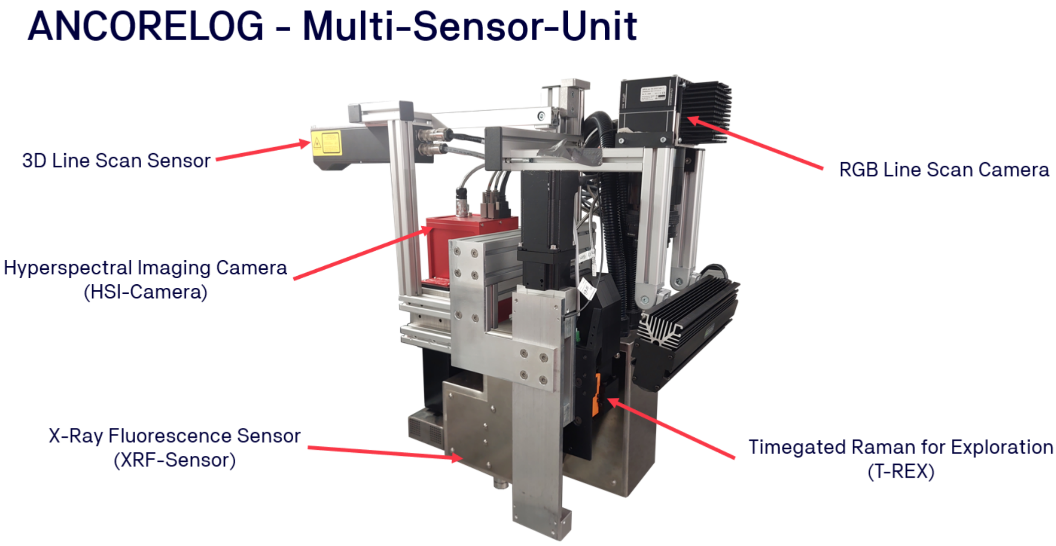


FIG 1 – Sensors equipped in the ANCORELOG device.

RESULTS

The following data is the result of the processed data from the above-mentioned sensors:

- XRF: A continuous scan of the rock provided spectrograms every 20 cm. The data were transformed from cps to concentrations using a calibration factor determined for each element, based on the elemental lab analysis provided by the company. This was performed for Cu, Fe, As, and Zn, and additionally for Al and Mg. These last two elements are not recognisable with XRF, but their abundance can be estimated based on the behaviour of Fe, Ti, and Ca. Figure 2 shows the correlation of the average calculated value of Cu every 2 m against the laboratory value given by the company through atomic absorption spectrometry.
- HSI: Mineral distribution maps for the recognisable minerals were continuously produced for all the rock samples. Based on the lithological interpretation given by the company, classification models using machine learning were created, so that future non-interpreted cores will be automatically categorised based on the HSI-mineral composition and distribution. Figure 3 compares the RGB images against the HSI images, allowing not only the determination of mineral distribution but also the identification of minerals present within veins and infills.
- RGB: Using RGB a high resolution digital lithotec data is created. Based on the RGB image and identifiable grain borders, an AI image segmentation was prepared to describe the distribution and granulometry for 'mineralised' grains. Such mineralised grains were identified using the visual criteria of a project geologist as well as Raman data.

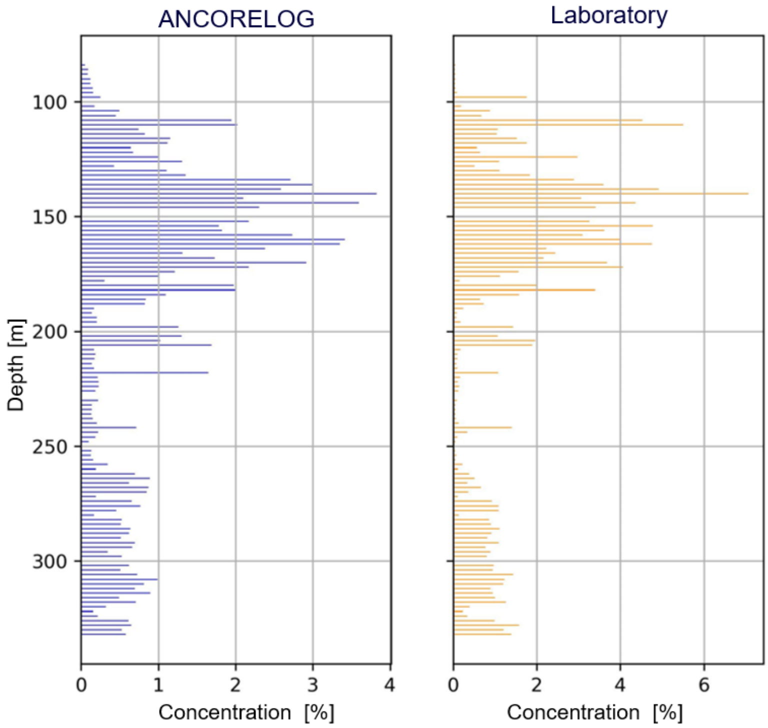


FIG 2 – Comparison of Cu concentration derived from XRF against laboratory analysis (atomic absorption spectrometry). Confidential source, further information on request.

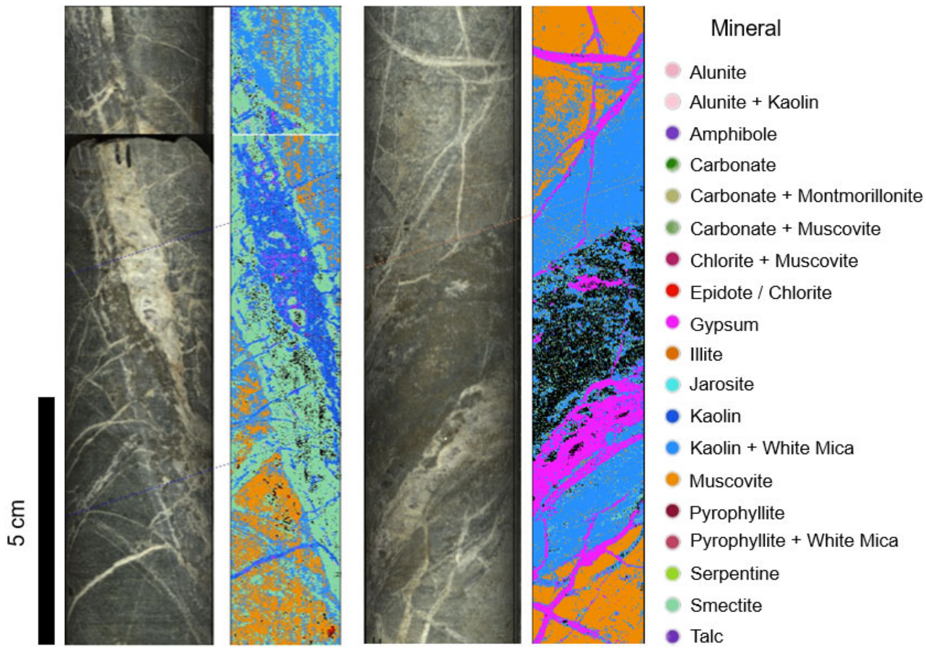


FIG 3 – Comparison between RGB and HSI based images highlighting mineral distribution. Confidential source, further information on request.

CONCLUSIONS

The implementation of multi-sensor-based core logging broadens the information available from the deposit and is highly valuable when used in the exploration stage by providing a fast pool of information, reducing decision-making time.

The accuracy of the XRF calibration and HSI lithological and alteration classification models is improved by a higher volume of laboratory and geological data as well as shorter intervals of them.

It is worth noting that ANCORELOG performs a 2D scan of the rock (only on the surface), while the laboratory analysis usually considers the homogenised rock bulk for a given interval. However, this information is obtained with a significantly increased spatial resolution compared to laboratory drill cores analysis.

ACKNOWLEDGEMENTS

The authors would like to thank the European Institute of Innovation and Technology (EIT), a body of the European Union under the Horizon 2020, the EU framework Program for Research and Innovation, for funding sensor developments in the projects ANCORELOG (Grant N°17028) and TREX (N° 19122). We want to extend our appreciation to DMT for funding and supporting the development of ANCORELOG, as well as the guidance provided by the DMT Natural Resources Division leadership team through a structured innovation process.

REFERENCES

Bauer, C, Wagner, R, Orberger, B, Firsching, M, Ennen, A, Garcia Piña, C, Wagner, C, Honarmand, M, Nabatian, G and Monsef, I, 2021. Potential of dual and multi-energy XRT and CT analyses on iron formations, *Sensors*, 21(7):2455. https://doi.org/10.3390/s21072455

Bauer, C, Wagner, R, Orberger, B, Garcia-Piña, C, Meima, J, Firsching, M, Merk, S, Rybok, L, Hyypio, R, Wagner, C, Boudouma, O, Siahcheshm, K, Kaminski, C, Lindstrom, H and Alamaki, M, 2022. Powerful laboratory and real-time examination tools for copper porphyry exploration, in International Mineral Processing Council (IMPC) Asia-Pacific Congress 2022. https://publica.fraunhofer.de/handle/publica/428779

Havisto, J, Lindström, H, Uusitalo, S, Heilala, B, Muller, S, Pons Perez, J M and Garcia Piña, C, 2021. Time-gated Raman spectroscopy as mineral analysis tool in multi-sensor Ancorelog drill core logger, in *Proceedings of the 11th International Conference on Advanced Vibrational Spectroscopy: Abstracts*, p 198.

Orberger, B, García-Piña, C, de Waard, B, Rybok, L, Hyypiö, R, Prudhomme, A, Capar, L, Lindström, H, Uusitalo, S, Alamäki, M, Kaminski, C, Meima, J and Merk, S, 2022. LIBS, XRF and Raman sensors for optimal bauxite sorting, in *Proceedings of IMPC Asia-Pacific 2022,* pp 437–462 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Teixeira Mendes, P, Barnabé, P, Koch, P, Pirard, E, Garcia Piña, C, Rybok, L, Bachmann, C, Pons, J M, Perez and Videira Vazquez, J C, 2021. Multisensor drill core logging integrating XR F and SWIR sensors to support machine learning, *EAGE: Mineral Exploration Symposium*, pp 1–3.

Increasing production systems availability through remote support discipline

S Glover[1], A Innis[2], A Bye[3] and B McCarthy[4]

1. Imvelo, Brisbane Qld 4000. Email: sharna.glover@imvelo.ai
2. Imvelo, Brisbane Qld 4000. Email: aaron.innis@imvelo.ai
3. Imvelo, Perth WA 6000. Email: alan.bye@imvelo.ai
4. Imvelo, Perth WA 6000. Email: brendan.mccarthy@imvelo.ai

ABSTRACT

Technology adoption in the mining industry has been steadily increasing over the past decade, driven by the need to improve operational efficiency, safety, sustainability, and profitability. As mining companies wish to implement solutions to improve mining safety and productivity, various technologies are being integrated into mining operations to enhance processes, reduce risks, and optimise resource utilisation.

Adoption of new technologies such as autonomous trucks requires a strong focus on foundational operational technology (OT) and a systems-thinking approach. OT support is critical however, OT is traditionally not considered or integrated into standard maintenance activities. Consequently, sourcing and applying service support to OT systems in real-time has posed significant challenges to date.

Neglecting the monitoring and upkeep of these operational technologies and equipment can lead to a host of adverse consequences. Operating instability becomes more prevalent, necessitating reactive measures, and the vulnerability to cybersecurity threats increases significantly.

To address OT monitoring and maintenance challenges, a systems wide mindset and remote support discipline must be utilised. Remote operations support refers to real-time, 24/7 monitoring, control and support of site OT: network, production systems, maintenance systems, enterprise systems and mobile and fixed plant through a single interface remote from site.

The presence of a disciplined team, grounded in a systems-oriented approach, is of the utmost importance to remote monitoring, given the intricate interdependencies of OT systems. The ability to understand the relationships among multiple systems, coupled with the capacity to distinguish between symptoms and root causes, assumes a pivotal role in operations.

Through diligent monitoring and the astute understanding of system thresholds, remote operations support can actively identify and alleviate constraints, in turn, serving as the enabler for transformative advancements in technology output.

INTRODUCTION

The adoption of innovative technologies is a critical enabler in unlocking the highest levels of productivity, efficiency, and safety within the mining industry. As the industry faces mounting challenges such as environmental, social, and governance (ESG) commitments, license to operate, and resource depletion, integrating advanced technologies across the whole of mine is a necessity to ensure seamless operations which maximise output. However, too often companies are overlooking and neglecting the requirements needed to maximise operational technology (OT) efficiency, thus not realising the full benefit the technology has to offer. By utilising effective remote support discipline to support OT, miners will achieve a significant increase in system performance and overall productivity.

Technology adoption in mining

Over the last decade, there has been a significant upward trend in the adoption of advanced, innovative technologies across the whole mine value chain. Driven by the need to improve operational efficiency, safety, sustainability and profitability, various technologies are being integrated into mining operations to enhance processes, reduce risks and optimise resource utilisation (Ediriweera and Wiewiora, 2021).

In particular, the industry has seen a significant investment in the adoption of operational technologies. Operational technology (OT) is defined as the software and hardware which is used to monitor, control and industrial processes, systems and devices (Gartner, 2024). OT encompasses the mine network communications, radios, servers, switches, PLCs etc, and allows real-time data collection, and in turn real-time decision-making regarding crucial mine assets.

Some key areas of operational technology adoption in mining include:

- Automation and robotics:
  - Automation technologies, such as autonomous haul trucks and drilling equipment, are being used to improve efficiency in tasks like ore extraction, material transport, and drilling. The uptake of these technologies is driven by labour shortages and they reduce the need for human intervention in potentially hazardous environments, while enabling continuous operations. Globally, autonomous haulage systems (AHS) have an unmatched safety record, with zero injured or fatalities over 15 years of operation, with more than 8 billion tonnes (Bt) hauled. The global mining automation market is forecast to grow at a 7.2 per cent compound annual growth rate (CAGR) from US$3.6bn in 2024 to US$5.1bn in 2029 (MarketsandMarkets, 2024).
- Digital and connected:
  - Smart devices and sensors, such as wearable tech and proximity sensors, are strategically positioned throughout mining sites gather real-time data on equipment performance, environmental factors, and worker safety. This information is pivotal for predictive maintenance, enhancing equipment efficiency, and ensuring the safety and well-being of employees, while creating operational cost reductions (GlobalData, 2023).
- Remote monitoring and control:
  - Remote monitoring and control systems allow operators to manage mining equipment and processes from central or remote locations. This minimises the exposure of workers to hazardous conditions and enables rapid response to issues.
- Big data and analytics:
  - The mining industry generates vast amounts of data, which can be analysed to gain insights into production processes, equipment performance, and geological conditions. For example, in 2018 Rio Tinto's Iron-Ore operations created 2.4 terabytes of data every minute across 16 mines, 1500 km of rail and three ports, from mobile equipment and sensors (Deloitte, 2024). This data-driven approach helps in making informed decisions to optimise operations and reduce costs.
  - The global mining industry is expected to spend US$1.4bn annually on data analytics by 2030 (ABI Research, 2023). Furthermore, the information and communications technology market within the global mining industry is expected to grow at a CAGR of 12.36 per cent from US$46.93bn in 2022 to US$84.06bn in 2027 (GlobalData, 2024).

Further operational technologies are in Table 1.

Operational technologies are not merely tools but investments with the potential to yield substantial returns. By deploying OT solutions, industries can significantly enhance the availability, throughput, and overall productive capacity of their production systems (Fisher and Schnittger, 2012). Whether in traditional or autonomous systems, OT serves as a linchpin for achieving operational excellence and driving business success. However, OT is not typically given much consideration in regard to monitoring and maintenance. Consequently, OT is typically not well managed.

TABLE 1
Operational technologies

Layer 1	Layer 2	Layer 3
Autonomous mining equipment	Autonomous haulage systems	AHT health (onboard equipment)
		Screens
		Sensors
		Applications
		GPS
	Autonomous drills	Screens
		Sensors
		Applications
		GPS
	Semi-autonomous dozers	Screens
		Sensors
		Applications
		GPS
	Fixed infrastructure	System servers
		System database
		GPS base stations
Fleet management and machine guidance systems	Drill guidance	Screens
		Sensors
		Applications
		GPS
	Dozer guidance	Screens
		Sensors
		Applications
		GPS
	Excavator guidance	Screens
		Sensors
		Applications
		GPS
	Truck	Screens
		Sensors
		Applications
		GPS
	All additional ancillary machinery	Screens
		Sensors
		Applications
		GPS

Operational technology networks	Wireless networks	PMP links PTP links Mesh data radio Switches Solar controller GPS (trailer)
	Fixed networks	Distribution switches Core switches Access switches
Operational technologies – safety systems	Driver fatigue management systems	Application Fatigue device status GPS Eye tracking sensors
	Collision avoidance systems	CAS major components
	Digital/analogue radio (2-way)	PTP links Switches

Operational technology – an investment in productivity

While there is substantial potential uplift from investing in OT, neglecting the monitoring and maintenance of OT systems can have severe repercussions. The implications of inadequate OT management, though not always apparent to mining operators, are multifaceted and far reaching, and can have severe consequences on various aspects such as safety, ESG commitments, cyber risks, productivity, and asset management costs. Addressing these risks requires a proactive approach to OT monitoring and maintenance which prioritises the reliability and performance of OT systems, while reducing technology downtime.

Traditional OT monitoring and maintenance practices typically utilise a siloed approach and do not align with technology-based events. Understanding OT capabilities and underpinning it with people and process in a systems wide mindset is critical to fully capitalise on the benefits these solutions bring. The approach to implementing any OT must be founded in a well formulated and implemented operational readiness plan that allows data to be used thereon for continuous improvement (McNab and Garcia-Vasquez, 2011).

For example, despite their significant investments, many leading miners such as Vale and Glencore have not yet seen substantial bottom line growth from their investments in OT due to their lack of ability and maturity when implementing a complex system of technologies (ABI Research, 2023). In contrast, ABI Research’s (2023) research found that BHP and Rio Tinto have both seen significant value uplift from OT which can be attributed to their successful integration and use of real-time data analytics to monitor and maintain such technologies across multiple facets of the mine.

Hence, maintaining uninterrupted operations through a robust systems wide approach to monitoring and proactive maintenance strategies is imperative for achieving optimal returns on OT investments.

Remote support discipline

In order to fully realise the benefits of OT, a systems wide mindset and one-team approach must be utilised in order to collapse the time between a technology-based event (such as AHS downtime) and the restoration of operations.

At the centre of this multifaceted approach sits remote support discipline and Technology Remote Operating Centres (TROC). Through the centralisation of support functions into a single nerve centre which aggregates and digests data collected from OT, TROCs facilitate 24/7 core systems health monitoring and incident management. The TROC also coordinates all technology changes that are going to be implemented at the site in alignment with operational downtime periods.

To establish a successful TROC, multiple OT maintenance and monitoring practices must be taken, including:

1. Enhanced monitoring protocols: a systematic increase in the monitoring of all solution elements must be implemented to enable early detection of potential issues.
2. Introduction of a technology support role: a innovative technology support role must be embedded in frontline operations. This role focuses on proactive monitoring and rapid response to technology-related issues.
3. Automated threshold alerts: identification and establishment of operational thresholds, coupled with automated alerts, will support proactive responses to potential challenges.
4. Decision assistance and automation tools: integration of decision assistance and automation tools to empower control teams to make informed decisions swiftly.
5. Development of routines and processes: rigorous development and adherence to standardised routines and processes must be instituted to enhance operational stability and efficiency.

Disciplined teams is key to amplifying performance

In the realm of remote operations, the efficacy of well-disciplined teams in executing tasks remotely stands as paramount. This capability is not merely advantageous but rather indispensable for amplifying performance levels within technological landscapes. Achieving this proficiency involves a multifaceted approach encompassing various strategies to achieve advanced practice as seen in Figure 1. Remote support teams must engage in deep diving exercises to gain comprehensive insights into the intricacies of technological systems, including both mine site and technology constraints (Shimaponda-Nawa and Nwaila, 2024). These teams must also grasp the intricacies of system usage and differentiate between symptoms and root causes of issues to address them effectively (Farrelly and Records, 2007). Delving into root causes rather than merely addressing surface-level symptoms allows remote teams to implement more effective solutions. By cultivating a systems mindset, remote support teams can grasp the underlying mechanisms and interactions within intricate OT systems, discerning how they function and how they are utilised in practical contexts.

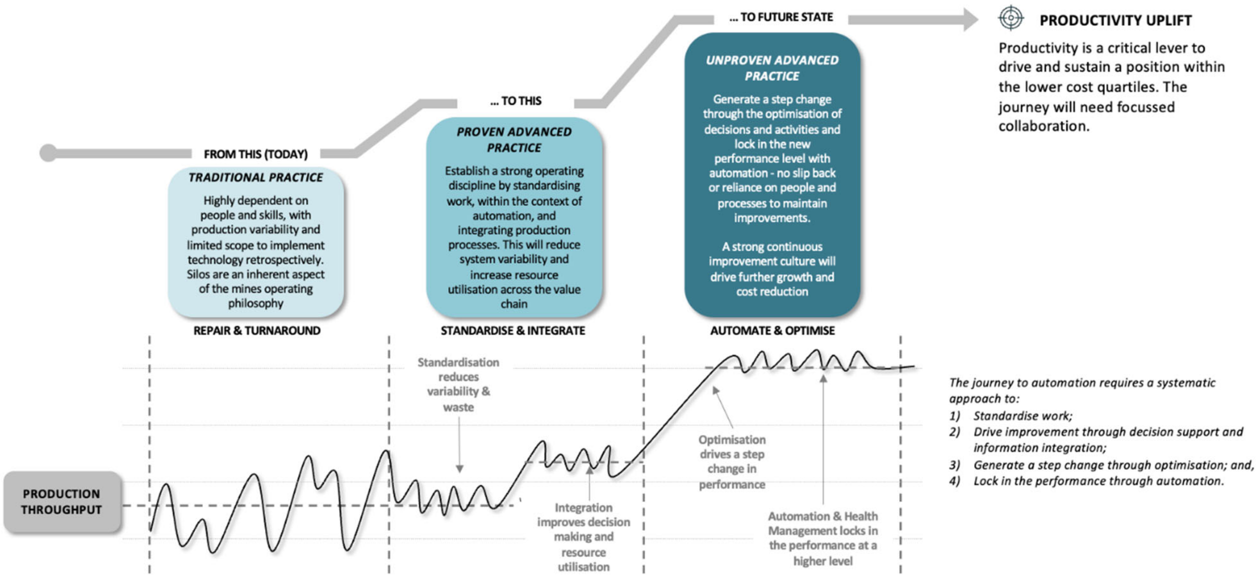


FIG 1 – Disciplined approach to locking in performance at a higher level.

Moreover, remote support teams are key to the early identification and alleviation of constraints within technological systems which leads to transformative outcomes. Each instance of constraint discovery presents an opportunity for learning, application of the knowledge gained, and subsequent improvement, fostering a culture of continuous enhancement (Shimaponda-Nawa and Nwaila, 2024). Through the iterative application of the *Acquisition + Application = Transformation* formula, remote support teams consistently drive towards improved performance, perpetuating a cycle of disciplined and sustained improvement.

Through unprecedented access to information and technology, we can realise a significant improvement in productivity by focusing our efforts on high value initiatives that reduce variability and unlock latent capacity (Shimaponda-Nawa and Nwaila, 2024).

Industry case study

An industry case study demonstrated that a site, four years after implementing AHS and following a sustained period of satisfactory performance, made a strategic decision to transition to a fully autonomous haulage system. This transition required several months of preparation. Shortly after the fully autonomous site went live, an unexpected challenge emerged in the form of a wireless network outage within hours of operation.

Upon the initial assessment of the issue a comprehensive triage was conducted to contain the problem temporarily, allowing the system to persist in a degraded state. Despite these efforts, the elusive nature of the root cause posed a persistent challenge.

Over an 18 month duration, recurrent P1 and P2 OT wireless network issues besieged the system, resulting in prolonged and frequent downtimes totalling over 10 hrs. This adversity gave rise to heightened tensions among support teams, maintenance personnel, and production units as the quest for identifying the underlying causes of the disruptions intensified.

At a critical juncture, the operational efficiency faced a substantial setback, with a deficit amounting to tens of millions of dollars relative to production targets. The once formidable stockpile, present upon site arrival, had substantially diminished.

To resolve the ongoing downtime issues, a 24/7 remote support function led by technology specialists was established across a 12 week program. By implementing newly developed routines and processes, coupled with adopting a systems mindset and comprehensive understanding of constraints, the TROC support teams were able to identify numerous contributory factors:

- Fragmented integration of technology teams led to inefficient collaboration with production/maintenance units, hindering effective operations.
- Operational blind spots emerged due to a limited understanding of the system's usage, resulting in a lack of synchronisation between operational components and inefficiencies.
- Inadequate monitoring infrastructure, characterised by insufficient monitoring of critical services and substandard monitoring tools, compromised the ability to promptly detect and address issues:
    - Additionally, inconsistencies in organisational processes highlighted the inadequacy of standardisation efforts, contributing to operational instability and inefficiencies.
- Neglect of critical processes, such as unsafe trailer movements with the power on, exacerbated network instability and safety concerns. Furthermore, unplanned trailer movements further compounded operational challenges and disruptions.

The impact of technology on the Autonomous Haulage System (AHS) was assessed by measuring truck stoppages, with a target of 0.5 stops per truck per hour, translating to 396 stoppages per 24 hr shift for a fleet of 33 trucks. One significant factor contributing to truck stoppages was the availability of the supporting wireless network, which initially stood at 93 per cent, below the target of 99.8 per cent. By implementing disciplined standardisation, routines, and remote support team monitoring, network availability was improved to 99.9 per cent. This enhancement in network reliability contributed to reducing truck stoppages from an average of 1300 per day to 350 per day, representing a 73 per cent reduction.

The enhancement of network availability and reduction of truck stoppages achieved through a 12-week program led to a significant increase in operational efficiency. Specifically, the improvement resulted in an uplift of annualised operational hours from approximately 5000 hrs to 6200 hrs, representing a 25 per cent increase in production as seen in Figure 2.

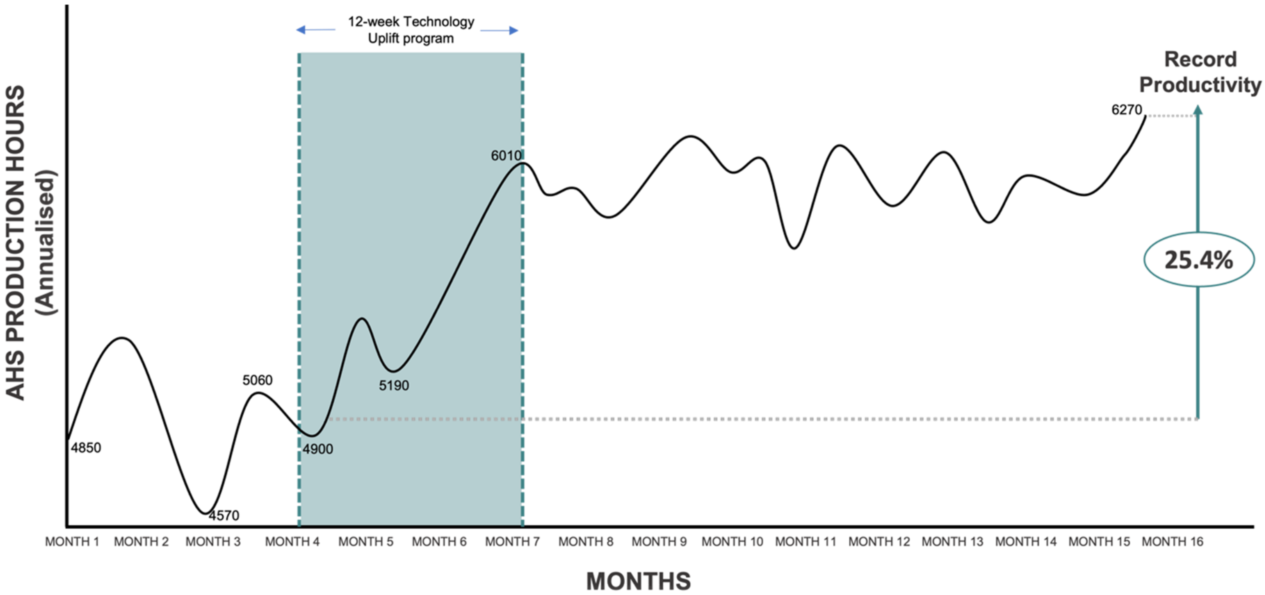


FIG 2 – Production uplift as a result of technology uplift.

The analysis significantly benefited from the rigorous operational discipline upheld by the TROC, bolstered by refined routines and processes. These were further complemented by enhanced monitoring protocols, automated threshold alerts, and decision assistance and automation tools, collectively ensuring a comprehensive and proactive approach to support operations.

Only through the implementation of a TROC support function was the site able to return to stable operations, with a significant reduction in technology related downtime, reduced frequency of P1/P2 events, as well as reduced time to restore services from any P1/P2 events.

Four key principles to improve remote support discipline

The value of remote support discipline cannot be overstated. It’s essential to recognise that operational technologies are often not a plug-and-play system; challenges are inevitable. However, the key lies in efficiently resolving issues that may arise within a shortened time frame. In order to achieve this, there are four key principles that organisations can utilise to aid in optimising their remote support discipline, minimising downtime, and delivering superior service to their stakeholders:

1. Ensure capability is underpinned with system thinkers who can view systems holistically. This broader perspective is crucial for identifying and removing constraints that impede problem resolution.
2. Develop the ability to distinguish between symptoms and underlying causes. This skill, coupled with a systems thinking approach, facilitates more accurate diagnoses and targeted solutions.
3. Focus efforts on understanding and eliminating constraints. By addressing root causes rather than surface-level issues, remote support teams can achieve more sustainable and effective outcomes.
4. Establish routines and adhere to them rigorously. Consistent practices contribute to efficiency, reliability, and proactive problem-solving, ultimately enhancing the effectiveness of remote support operations.

CONCLUSION

Operational technologies play a pivotal role in shaping the efficiency, safety, and productivity of production systems, while serving as a linchpin for achieving operational excellence and driving business success. Recognising OT as a strategic investment, optimising its simplicity, and ensuring high availability through diligent remote monitoring and maintenance strategies are essential steps towards unlocking its full potential. By prioritising the effective implementation and management of OT through the use of remote support discipline, industries can navigate the complexities of modern production environments with confidence to drive sustainable growth and success.

REFERENCES

ABI Research, 2023. Mining Firms Data Analytics Spend Will Reach US$1.4 Billion in 2030 to Improve Yields and Operations, ABI Research. Available from: <https://www.abiresearch.com/press/mining-firms-data-analytics-spend-will-reach-us14-billion-in-2030-to-improve-yields-and-operations/> [Accessed: 3 April 2024].

Deloitte, 2024. Tracking the trends 2024, Deloitte. Available from: <https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Energy-and-Resources/us-trend-8.pdf> [Accessed: 2 April 2024].

Ediriweera, A and Wiewiora, A, 2021. Barriers and enablers of technology adoption in the mining industry, *Resources Policy*, 73:102188. https://doi.org/10.1016/j.resourpol.2021.102188

Farrelly, C and Records, L, 2007. Remote Operations Centres—Lessons from Other Industries, *Australian Mining*, 65.

Fisher, B and Schnittger, S, 2012. Autonomous and Remote Operation Technologies in the Mining Industry, Benefits and Costs BAE Report, 12.1.

Gartner, 2024. Operational Technology, Gartner. Available from: <https://www.gartner.com/en/information-technology/glossary/operational-technology-ot> [Accessed: 2 April 2024].

GlobalData, 2023. Internet of Things (IoT) in Mining – Thematic Intelligence, GlobalData. Available from: <https://www.globaldata.com/store/report/iot-in-mining-theme-analysis/> [Accessed: 2 April 2024].

GlobalData, 2024. Mining Sector ICT market size and forecast (by country, it solution area and vertical) to 2027. GlobalData. Available from: <https://www.globaldata.com/store/report/mining-sector-ict-market-analysis/> [Accessed: 2 April 2024].

MarketsandMarkets, 2024. Mining Automation Market, MarketsandMarkets. Available from: <https://www.marketsandmarkets.com/Market-Reports/mining-automation-market-257609431.html> [Accessed: 2 April 2024].

McNab, K and Garcia-Vasquez, M, 2011. Autonomous and remote operation technologies in Australian mining, Centre for Social Responsibility in Mining (CSRM)-Sustainable Minerals Institute, University of Queensland.

Shimaponda-Nawa, M and Nwaila, G, 2024. Integrated and intelligent remote operation centres (I2ROCs): Assessing the human–machine requirements for 21st century mining operations, *Minerals Engineering*, 207:108565. https://doi.org/10.1016/j.mineng.2023.108565

Practical applications of large language models in mining

B Gyngell[1] and P Culvenor[2]

1. CEO, Hevi, Sydney NSW 2026. Email: brad.gyngell@hevi.app
2. CFO, Access Mining, Brisbane Qld 4101. Email: paul.culvenor@accessmining.com.au

ABSTRACT

Large language models (LLMs) have generated a lot of hype since ChatGPT was released in early 2023. In essence, they allow people to interact with computer systems through natural language and have the ability to generate highly complex text, images and videos (Patil and Gudivada, 2024).

It is clear that this technology has significant potential, however most mining companies have not yet found practical applications for it within their operations.

In this paper, we present a range of such applications along with the tactical considerations associated with developing and implementing them. We have identified use cases across a variety of operational and functional areas within the mining industry and evaluated them based on their potential business value and ease of implementation.

Firstly, we provide an overview of how LLMs work and a review of how LLMs are being applied in other industries to provide best practice inspiration for mining.

Next, we present a list of possible applications in mining and a critical assessment of each use case. This section also includes a technical deep dive into the different methodologies for developing the technologies as well as an analysis of barriers to adoption within mining organisations.

Finally, we share a discussion of the potential path forward for LLMs in mining and the impact they could have on the industry. We analyse the potential differences between early adopters and laggards in the artificial intelligence (AI) space.

This research draws on interviews and surveys with artificial intelligence experts as well as mining subject matter experts to connect cutting edge thought leadership with the specific problems faced by our industry.

INTRODUCTION

The advent of various sectors, with ChatGPT's release in early 2023 marking a significant milestone demonstrated an unprecedented ability to understand and generate complex text, images, and videos through conversational interfaces (Patil and Gudivada, 2024). This paper explores the untapped potential of LLMs within the mining industry, a sector yet to fully capitalise on these technological advancements.

Despite the transformative possibilities LLMs present, practical applications in mining operations remain largely unexplored. Our research aims to bridge this gap by presenting a suite of applications tailored to the mining context. We assess these applications against two critical dimensions: their potential business value and the ease of implementation, providing a pragmatic guide for mining companies considering the integration of LLMs into their workflows.

The structure of this paper is designed to navigate the reader through the intricacies of LLMs, from a foundational understanding to specific industry applications. We commence with a technical overview of LLMs, followed by a review of their applications in other industries to inspire best practices for mining. Subsequently, we delve into a curated list of mining-specific applications, accompanied by a thorough evaluation of each use case.

To ensure our findings are grounded in reality, we have drawn upon insights from interviews and surveys with AI experts and mining subject matter experts. This approach allows us to align cutting-edge AI developments with the unique challenges faced by the mining industry. By doing so, we aim to illuminate a path forward for the adoption of LLMs in mining, considering the strategic implications for early adopters and the potential consequences for laggards in the AI space.

OVERVIEW AND TECHNICAL FOUNDATIONS OF LARGE LANGUAGE MODELS

Large language models represent a significant leap forward in the field of artificial intelligence, particularly in the realm of natural language processing. These models are designed to understand and generate human-like text by leveraging deep learning algorithms and extensive training data sets. The ability of LLMs to interact with users in a conversational manner has opened up new avenues for human-computer interaction, making them particularly intriguing for industries such as mining, which are traditionally less associated with cutting-edge AI applications (Patil and Gudivada, 2024).

At their core, LLMs are sophisticated prediction models that take a string of text as input and predict the most likely subsequent text. This predictive capability is what makes them powerful 'completion models.' They are trained to complete a given section of text by generating additional text that follows logically and contextually from the input. This is achieved through the use of transformer-based neural network architectures, which employ self-attention mechanisms to process sequences of words. By predicting the probability distribution of a subsequent word or phrase, LLMs can generate coherent and contextually relevant continuations, making them adept at tasks such as answering questions, composing emails, or even drafting technical documents (Naveed *et al,* 2023).

The mathematical foundation of LLMs involves training these models on large corpora of text data using algorithms that adjust the weights of the neural network. This training process is guided by a loss function, which quantifies the difference between the predicted text output and the actual text. Through iterative optimisation techniques such as stochastic gradient descent, the model's parameters are fine-tuned to minimise this loss function, thereby improving the model's predictive accuracy (Liu *et al,* 2024).

For the mining industry, the application of LLMs as completion models holds particular promise. The ability to generate accurate predictions and completions can be harnessed to automate and enhance various documentation processes, from report generation to compliance checks. However, the deployment of LLMs in such a specialised field requires careful consideration of the technical and operational nuances. The subsequent sections will explore the practical applications of LLMs in mining, the methodologies for their development, and the challenges to their adoption within the industry.

LLMS IN OTHER INDUSTRIES – A SOURCE OF INSPIRATION

Customer support

Intercom's AI bot Fin exemplifies the integration of LLMs to enhance user experience. Fin interacts with customers using natural language, providing immediate responses to inquiries and streamlining the support process. By utilising LLMs, Fin analyses customer messages, discerns intent, and retrieves relevant information from a knowledge base to offer precise answers (Intercom, 2024).

The value created is twofold: customers benefit from swift resolution times, and support teams are relieved from handling repetitive queries, allowing them to concentrate on more complex issues. mining companies could adopt similar AI-driven support systems to manage routine inquiries related to site operations, equipment maintenance, or safety protocols, thus improving efficiency and worker satisfaction.

Healthcare

Heidi Health's application of LLMs demonstrates the potential for AI to reduce administrative burdens. Automating tasks such as appointment scheduling, patient follow-ups, and record-keeping, Heidi Health enables medical professionals to dedicate more time to patient care. The AI interprets and organises textual data, ensuring that administrative tasks are executed with precision and in compliance with healthcare regulations (Heidi Health, 2024).

The value lies in increased operational efficiency and enhanced patient outcomes. Mining companies could implement LLMs to automate safety reports, regulatory compliance documentation, and personnel scheduling, enhancing safety and compliance while reducing administrative overhead.

Legal sector

CaseText CoCounsel has revolutionised legal document analysis and management. This AI tool performs document review, deposition preparation, legal drafting, and timeline creation in minutes—with trustworthy results. By parsing complex legal documents and identifying key clauses, CaseText CoCounsel accelerates the contract review process and reduces the likelihood of human error (Casetext, 2024).

The value for legal professionals is clear: more time for strategic work and less time on routine document scrutiny. Mining companies could leverage this technology for contract management in procurement and partnership agreements, ensuring that terms are favourable and risks are mitigated.

Finance

PayPal has enhanced fraud detection by using inference LLMs powered by graphics processing units, which improved real-time fraud detection by 10 per cent while reducing server capacity nearly eight times. By analysing transaction patterns and customer communications, PayPal's AI system identifies anomalies that may indicate fraudulent activity (Levitt, 2023).

The AI's ability to process vast amounts of data quickly and accurately creates significant value by protecting financial assets and maintaining customer trust. Mining companies could apply similar AI-driven systems to monitor financial transactions and supply chain integrity, safeguarding against fraud and ensuring operational continuity.

Education

Khanmigo, an AI-powered personal tutor and teaching assistant from Khan Academy, offers a unique approach to learning. Unlike other AI tools, Khanmigo doesn't simply provide answers; it patiently guides learners to discover the answer themselves. Integrated with Khan Academy's extensive content library, Khanmigo has been rated highly by Common Sense Media for its engaging and effective learning experience (Khan Academy, 2024).

For teachers, Khanmigo reduces busy work by assisting with lesson plans, quiz questions, and more. Mining companies could use similar AI applications for training and development, offering personalised learning paths for employees to advance their skills in line with industry advancements and company objectives.

LLMS IN THE MINING INDUSTRY – POTENTIAL APPLICATIONS

Regulatory compliance and incident response

Overview

Staying abreast of regulatory compliance and being prepared for incident response are critical components of operational management. Mine managers as well as health, safety, environment and community (HSEC) teams are tasked with the complex responsibility of understanding and adhering to a myriad of acts, regulations, and standards, while also ensuring that site procedures and policies are up-to-date and enforceable.

Furthermore, in the event of an incident, swift and appropriate action is required to align with regulatory requirements and to minimise impact. An LLM-based system designed for regulatory compliance and incident response can provide invaluable support in these areas, offering real-time assistance, ensuring legal conformity, and guiding managers through the intricacies of incident management.

How the solution could work

An LLM-based system for regulatory compliance and incident response would act as an intelligent assistant for Mine Managers and HSEC Managers. The system would be programmed with up-to-date knowledge of relevant acts, regulations, and standards. Using natural language processing, the LLM would interpret legal texts and provide concise summaries and actionable guidance. For compliance, the system could review site procedures and policies, comparing them against current legislation to ensure alignment. In the event of an incident, the LLM would guide managers through the necessary response steps, ensuring that all regulatory requirements are met promptly.

Value provided

This solution would serve as a real-time reference tool, enabling managers to make informed decisions quickly, which is especially critical during incident response. By ensuring that site procedures are always in compliance with the latest regulations, the system would help prevent legal infractions and potential fines.

In the case of an incident, the LLM's guidance would help managers take the correct actions to mitigate risks, manage communications, and document the response in accordance with regulatory expectations, thereby safeguarding the company's reputation and legal standing.

Implementation feasibility

To implement this system, a comprehensive database of relevant legal and regulatory documents would need to be compiled and regularly updated. The LLM would be trained on this database to understand the specific legal language and requirements of the mining industry. Integration with the company's existing policy management and incident response systems would be necessary to provide seamless functionality.

While the initial set-up may require a significant investment in terms of data collection and system training, the ongoing updates and maintenance could be automated to a large extent. The feasibility of this system is high, given the clear structure of legal documents and the critical need for compliance in the mining industry. The system would be designed with a user-friendly interface to ensure that it is accessible and easy to use for managers who may not have specialised legal expertise.

Contract management and administration

Overview

Effective contract management and administration are pivotal for the mining sector, where contracts often represent significant financial commitments and complex legal arrangements. Site teams, while expert in their operational roles, may lack the time or legal expertise to manage these contracts meticulously, potentially leading to costly contractual disputes or oversights.

An AI-powered solution can transform contract management by providing an intuitive way for team members to interact with contract documents, understand their obligations, and identify out-of-scope requests that require additional billing.

Furthermore, LLMs can continuously monitor project communications and reports, intelligently identifying and flagging potential contractual issues before they escalate, such as the need to notify clients of claimable events.

How the solution could work

An LLM-based contract management system could employ Retrieval Augmented Generation (RAG) to serve both primary functions: interactive document search and automated report and email scanning. For document search, when users pose questions or seek clarifications, the LLM would instantly retrieve and synthesise information from the relevant contracts and legal documents, providing precise answers and guidance.

In terms of automated scanning, the LLM would continuously analyse incoming reports and emails, using RAG to cross-reference the contents with contractual obligations and terms. By understanding the significance of the text within the context of the contract, the LLM could identify potential issues or actions that need to be taken, such as notifying the client of claimable events. This dual functionality ensures that contractual obligations are proactively managed and that compliance is maintained across all communication channels.

Value provided

The introduction of an LLM into contract management provides substantial value by equipping site teams with the tools to interpret and adhere to complex contracts accurately. This capability ensures that all contractual obligations are met, variations are correctly billed, and potential disputes are minimised. The LLM's proactive monitoring can alert teams to actionable items, ensuring compliance with contract terms and safeguarding against financial losses due to unclaimed entitlements.

Implementation feasibility

The feasibility of deploying an LLM for contract management using Retrieval Augmented Generation (RAG) is quite promising, given that RAG circumvents the need for extensive pre-training on specific documents. This technology allows the LLM to pull the most relevant and up-to-date information from a document repository in real-time, which is crucial for providing accurate responses to contract-related queries and for monitoring communications effectively. However, the success of this implementation largely depends on the seamless integration of the LLM with the company's existing contract management systems and communication channels. This integration is critical to ensure that the LLM has comprehensive access to all necessary documents and data flows.

The design of the system must prioritise user-friendliness to encourage adoption by site teams who may not be technically inclined. Additionally, the document repository that the LLM relies on must be meticulously maintained and regularly updated to reflect the latest contractual changes and legal updates, ensuring the system's ongoing accuracy and relevance.

Bidding and tendering

Overview

In the competitive landscape of bidding and tendering for mining contracts, the ability to rapidly sift through extensive tender documents and evaluate opportunities against specific criteria is crucial. Large Language Models can automate this process, enabling contractors to efficiently assess the viability of a tender and ensure compliance with their policies.

By using LLMs to automatically draft departures from standard terms, contractors can align tender responses with their internal risk profiles and operational capabilities. This application of AI not only streamlines the tender review process but also enhances the quality and consistency of bid submissions.

How the solution could work

An LLM-based system for bidding and tendering would allow users to upload tender documents, which the AI would then analyse to extract key information. The LLM would be equipped to understand and interpret the complex language often found in these documents, including technical specifications, contractual obligations, and compliance requirements.

Users could input a set of criteria reflecting the contractor's policies and risk thresholds, and the LLM would evaluate the tender against these benchmarks. Additionally, the system could automatically generate departures or exceptions to the tender terms that are necessary for compliance with the contractor's policies.

Value provided

The use of LLMs in the bidding and tendering process provides significant value by reducing the time and resources typically required to review and respond to tenders. It ensures that all submissions are thoroughly vetted against the contractor's standards and compliant bids.

Furthermore, the ability to quickly draft departures helps contractors negotiate from a position of strength, with a clear understanding of their requirements and limitations. This level of analysis and preparation can give contractors a competitive edge in securing profitable contracts.

Implementation feasibility

Implementing an LLM system for bidding and tendering would involve integrating the AI with the contractor's existing document management and bid preparation workflows. The system would need to be designed with a user-friendly interface to facilitate ease of use by the tendering team. While the initial set-up may require customisation to match the contractor's specific criteria and policies, the adaptability and learning capabilities of LLMs mean that the system would become more efficient over time.

The investment in such a system is justified by the potential for more successful bids and the avoidance of costly contractual missteps. With proper integration and ongoing management, an LLM-based bidding and tendering system could become an indispensable tool for contractors in the mining industry.

Training and safety compliance

Overview

Mining operations are governed by stringent safety regulations. LLMs can be used to ensure compliance by interpreting safety procedures and generating easy-to-understand guidelines for employees. They can also create interactive training modules that adapt to the learning pace of each worker, similar to the educational applications seen with Khanmigo.

The business value lies in reducing accidents and ensuring regulatory compliance, which can save lives and avoid costly fines. Implementation is feasible as it leverages existing safety documentation and training materials to create a more engaging and effective learning experience.

How the solution could work

The proposed LLM solution for safety protocol compliance and training would function as an intelligent interface between the vast array of safety regulations and the mining workforce. Initially, the LLM would be trained on a comprehensive data set of safety protocols, regulations, and best practices specific to the mining industry.

Once trained, the LLM could interpret complex regulatory language and translate it into simple, actionable instructions for employees. For training purposes, the LLM could generate interactive modules that present safety scenarios and quiz workers on the best course of action, providing immediate feedback and additional information when needed.

Value provided

The value of such a system is multifaceted. Primarily, it would enhance the understanding and retention of safety protocols among the workforce, leading to a safer work environment and potentially reducing the number of accidents and incidents.

By ensuring that all employees are well-versed in safety procedures, the company could also demonstrate due diligence in compliance efforts, which could mitigate legal risks and reduce the likelihood of fines. Additionally, a well-trained workforce is more efficient and can contribute to a culture of safety that extends beyond mere compliance.

Implementation feasibility

Implementing this LLM-based safety training solution would involve several steps. The first would be to curate and digitise all relevant safety materials. Next, the LLM would need to be trained on these materials until it could accurately interpret and convey the information. The development of a user-friendly interface would be crucial to facilitate interaction with the system.

While the initial set-up and training of the LLM may require a significant investment of time and resources, the ongoing costs are likely to be low. Moreover, the modular nature of the training system means it can be updated and expanded as regulations change, providing long-term value. The ease of implementation would largely depend on the existing digital infrastructure and the company's commitment to adopting new technologies for safety training.

Hazard and incident reporting

Overview

LLMs can automate the incident reporting process by allowing employees to submit reports using natural language, which the AI can then process to extract key information and populate databases. This application creates value by improving the accuracy of incident reporting and analysis, leading to better safety outcomes. Implementation is feasible with the development of a user-friendly interface and integration with existing health and safety systems.

How the solution could work

An LLM-based hazard and incident reporting system would allow employees to report potential hazards and actual incidents directly through their existing two-way radios. Utilising voice-to-text technology, the system would convert spoken reports into text, which the LLM would then process.

The AI would be specifically trained to understand the nuances of spoken language in the context of mining operations, including any jargon or shorthand used by the workers. Once the report is transcribed, the LLM would identify and extract key details such as the nature of the hazard or incident, specific location, time, and any immediate actions taken.

Value provided

The integration of voice reporting via two-way radios would encourage more proactive hazard reporting by making it convenient for employees to report issues as soon as they are identified, without needing to return to a workstation or find a computer. This immediacy can lead to quicker responses to potential hazards, reducing the likelihood of incidents occurring.

For actual incidents, the system would ensure a rapid and accurate capture of details, which is critical for emergency response and subsequent analysis. The data collected would provide insights into common risks and inform strategies to prevent future occurrences.

Implementation feasibility

Implementing this voice-enabled LLM system would involve interfacing the AI with the radio communication network and ensuring reliable voice-to-text conversion in the noisy environment of mining operations. The system would need to be robust enough to handle various accents and speech patterns.

Training the LLM would require a data set of voice reports to fine-tune its understanding of mining communication. While integrating voice reporting into the existing safety management infrastructure presents additional technical challenges, the potential for significantly improved hazard and incident reporting makes it a compelling option for enhancing mine safety. The system's design would focus on user-friendliness to ensure widespread adoption and effectiveness in promoting a culture of safety and vigilance.

Preventative maintenance

Overview

Predictive maintenance is crucial in mining. LLMs can be used to process equipment logs and maintenance records, predict when maintenance is required, and generate work orders. This application is akin to the predictive analytics used in finance for fraud detection.

The business value is in preventing equipment failure, reducing downtime, and extending the life of expensive machinery. Implementation is feasible with the integration of LLMs into existing maintenance tracking systems.

How the solution could work

An LLM-based solution for equipment maintenance in mining would involve the AI analysing historical and real-time data from equipment logs and maintenance records. The system would learn patterns associated with equipment wear and failure, enabling it to predict when maintenance should be performed before a breakdown occurs.

The LLM would be integrated with the mining company's existing maintenance tracking systems, allowing it to process data from various sources, including sensors on the equipment, operator reports, and maintenance history.

Value provided

The primary value of this predictive maintenance system is the reduction of unplanned downtime, which can be extremely costly in terms of lost production and emergency repair expenses.

By accurately predicting maintenance needs, the system ensures that equipment is serviced only when necessary, optimising maintenance schedules and resource allocation. This not only extends the lifespan of the machinery but also enhances operational efficiency and safety.

Additionally, the system can help identify training opportunities for operators by highlighting recurring issues related to equipment misuse.

Implementation feasibility

The feasibility of implementing this LLM-based predictive maintenance system depends on the availability and quality of data. The more comprehensive and clean the data, the more accurate the predictions will be. Integrating the LLM with existing maintenance software may require some initial customisation and investment in information technology (IT) infrastructure. However, once in place, the system can be scaled and adapted to new equipment and technologies.

The ongoing maintenance of the system would involve regular updates to the LLM's training data to account for new equipment, changes in operation conditions, and evolving maintenance practices. With a strong commitment to digital transformation and data management, the implementation of this LLM solution can be a strategic move for mining companies looking to optimise their maintenance operations.

LLMS IN THE MINING INDUSTRY – EVALUATION OF OPPORTUNITIES

These opportunities were assessed based on their value to the company and the ease of implementation. The results are shown in Table 1 and Figure 1.

TABLE 1

Evaluation of opportunities for LLMs in mining.

Opportunity	Value to companies	Ease of implementation
Regulatory compliance and incident response	2	5
Contract management and administration	5	3
Bidding and tendering	2	3
Training and safety compliance	2	1
Hazard and incident reporting	4	2
Preventative maintenance	3	1

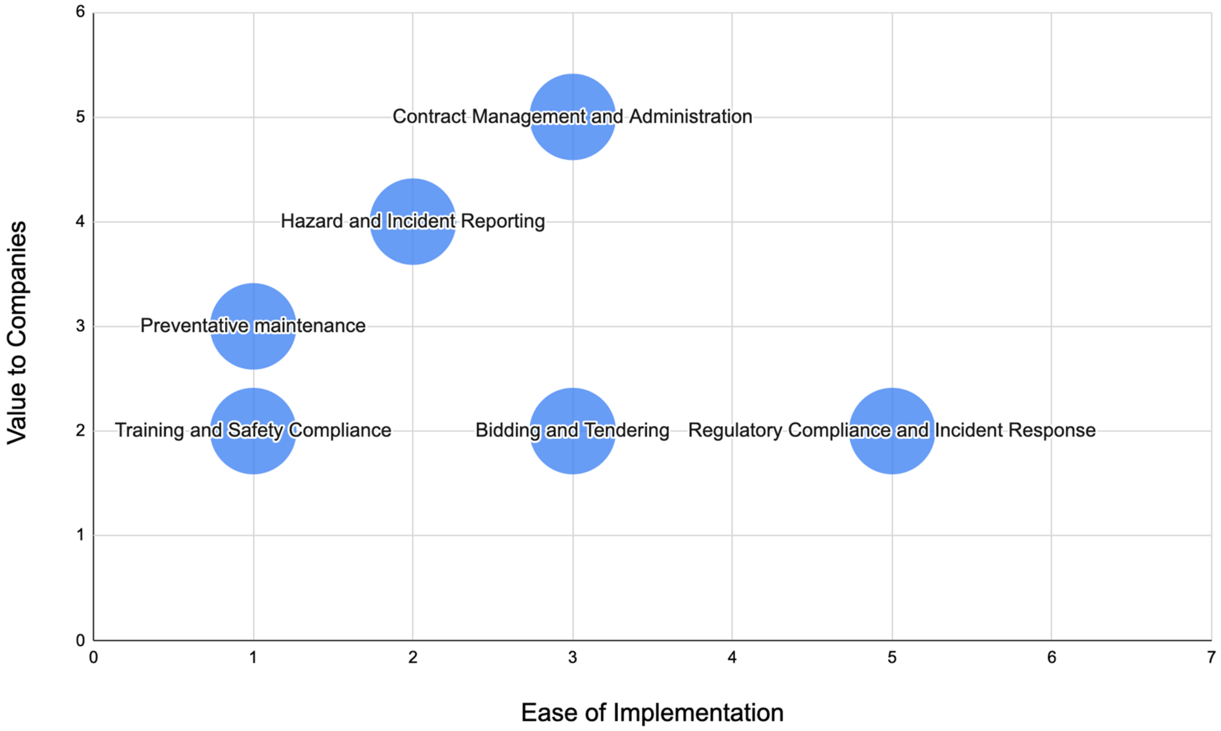


FIG 1 – Evaluation of LLM opportunities in mining.

CONSIDERATIONS FOR IMPLEMENTATION

Barriers to adoption in mining

The implementation of Large Language Models (LLMs) within mining organisations can encounter several barriers. One significant challenge is the resistance to change, as mining is an industry with established processes and a workforce that may be sceptical of new technologies. AI in particular requires a level of trust from users that can take a long time to build.

There is also the issue of technological integration, where existing IT infrastructures may not be compatible with the latest AI systems, requiring substantial upgrades or overhauls.

Data privacy and security concerns are paramount, given the sensitive nature of contractual and operational information in mining. Additionally, the accuracy and reliability of LLMs in interpreting complex and technical mining language can be a concern, as any misinterpretation could lead to costly mistakes.

Recommendations for overcoming barriers

To overcome these barriers, it is essential to engage in comprehensive change management strategies, including education and training programs that demonstrate the value and ease of use of LLMs. Pilot programs can help to showcase the benefits and allow for a gradual adaptation process and prove the accuracy of AI to build trust.

Ensuring that LLM solutions are compatible with existing systems or that they offer modular integration options can alleviate technological integration issues.

Rigorous data security protocols and clear communication about these measures can address privacy and security concerns. To ensure accuracy, LLMs should be fine-tuned with industry-specific data sets and validated by experts before full deployment.

Implementation opportunities afforded by LLMS

LLMs present unique implementation opportunities in the mining industry. They can serve as a new interface for digital systems, offering a more intuitive and natural way for less tech-savvy workers to engage with technology. By using conversational AI, workers can interact with complex systems through simple language, reducing the learning curve and increasing accessibility.

LLMs can also centralise knowledge, making it easier for employees to access information and expertise that would otherwise be siloed. Furthermore, the automation of routine tasks such as document analysis and report generation can free up skilled workers to focus on more critical, value-added activities. The adaptability of LLMs means they can be continuously improved to meet the evolving needs of the mining industry, making them a versatile tool for innovation and efficiency.

THE FUTURE OF LLMS IN MINING

The trajectory for LLM adoption in the mining industry points towards a gradual but inevitable integration as the benefits become more evident and the technology more refined. Early adopters are likely to be organisations that are already digitally mature and open to innovation.

These companies will pave the way, demonstrating the competitive advantages of LLMs, such as enhanced decision-making, increased efficiency, and improved compliance. As early adopters refine the use of LLMs and showcase their successes, latecomers will face increasing pressure to integrate these technologies to remain competitive.

The divide between early adopters and latecomers could become significant, especially if early adopters leverage LLMs to achieve substantial gains in productivity and risk management. Latecomers may struggle to catch up as they work through the initial barriers to adoption and the learning curve associated with implementing new technologies.

However, as the technology becomes more user-friendly and case studies of successful implementations proliferate, the barriers to entry will lower, allowing more widespread adoption across the industry.

In the long-term, the impact of LLMs on the mining industry could be transformative. LLMs have the potential to revolutionise how data is managed and utilised, leading to smarter and more agile operations.

They could also democratise access to information and expertise, allowing workers at all levels to make informed decisions based on a wealth of knowledge that was previously inaccessible. As LLMs become more integrated into the daily operations of mining companies, they will likely become a critical component of the industry's ongoing digital transformation, driving innovation and efficiency in an ever-evolving global market.

CONCLUSION

In conclusion, the exploration of Large Language Models (LLMs) within the mining industry, as detailed in this paper, reveals a significant potential for greater efficiency and reduced risk.

The applications of LLMs, ranging from regulatory compliance to contract administration, present opportunities to enhance decision-making and operational effectiveness.

Despite challenges such as resistance to change and technological integration, strategic implementation and a focus on overcoming barriers can lead to successful adoption.

As the industry evolves, LLMs stand to become a transformative force, driving the digital transformation of mining and offering a competitive edge to early adopters. The future of mining with LLMs promises a more informed, agile, and safer industry.

REFERENCES

Casetext, 2024. Meet CoCounsel [online]. Available from: <https://casetext.com/> [Accessed: 3 April 2024].

Heidi Health, 2024. AI medical scribe for all clinicians [online]. Available from: <https://www.heidihealth.com/> [Accessed: 3 April 2024].

Intercom, 2024. Resolve 50% of your support questions with our AI Chatbot [online]. Available from: <https://www.intercom.com/drlp/ai-chatbot> [Accessed: 6 April 2024].

Khan Academy, 2024. Meet Khanmigo, Khan Academy's AI Teaching Assistant [online]. Available from: <https://www.khanmigo.ai/> [Accessed: 2 April 2024].

Levitt, K, 2023. How Is AI Used in Fraud Detection? [online]. Available from: <https://blogs.nvidia.com/blog/ai-fraud-detection-rapids-triton-tensorrt-nemo/> [Accessed: 5 April 2024].

Liu, Y, He, H, Han, T, Zhang, X, Liu, M, Tian, J, Zhang, Y, Wang, J, Gao, X, Zhong, T and Pan, Y, 2024. Understanding LLMs: A comprehensive overview from training to inference, *arXiv (preprint)*, arXiv:2401.02038.

Naveed, H, Khan, A U, Qiu, S, Saqib, M, Anwar, S, Usman, M, Barnes, N and Mian, A, 2023. A comprehensive overview of large language models, *arXiv (preprint)*, arXiv:2307.06435.

Patil, R and Gudivada, V, 2024. A Review of Current Trends, Techniques and Challenges in Large Language Models (LLMs), *Applied Sciences,* 14(5):2074.

An autonomous IIoT-based monitoring systems for intelligent rock bolts in underground mines

P Hartlieb[1], M Varelija[2] and M Noeger[3]

1. Senior Scientist, Montanuniversitaet Leoben, 8700 Leoben, Austria. Email: philipp.hartlieb@unileoben.ac.at
2. PhD student, Montanuniversitaet Leoben, 8700 Leoben, Austria. Email: michel.varelija@unileoben.ac.at
3. PhD student, Montanuniversitaet Leoben, 8700 Leoben, Austria. Email: michael.noeger@unileoben.ac.at

INTRODUCTION

Rock bolts are important in underground mining as they provide support to the rock mass around the excavation. They are the most common reinforcement method in mining and civil engineering excavations. The length of the bolts, types and spacing between them can be varied, depending on the reinforcement requirements and the use case (Kolapo, Onifade and Praise, 2022).

The rock bolt provides safety and stability for the rock mass in the excavation area and they can be mechanically anchored, grouted, or friction anchored. They normally don't have a measurement option and there is a possibility that it failed without showing visible signs on the surface, especially in grouted rebar bolts where they can still have some residual strength. Therefore, support functionality can be lost without recognising it. To overcome that, sensors can be installed on all three previously mentioned bolt systems. Intelligent bolts with implemented measuring systems have a function of showing changes and indicating if there is some damage on the bolt. So, it can be said that intelligent rock bolts are regular bolts equipped with additional instruments which are helping us detect potential instabilities inside of the rock mass or malfunction of the bolt itself.

Changes in rock mass can be tracked, by measuring rock bolt reaction concerning the excavation response. Rock mass damage and instabilities are therefore measured in terms of rock mass deformation. Moreover, other additional information depending on the type of the sensor device could be collected. Based on such measurements, information about rock mass state can be derived. Different rock bolt types work at different reaction principles. Therefore, limitations on sensor application and information that can be extracted must be considered.

INTELLIGENT ROCK BOLTS

For mine operators, it is essential to identify and monitor potential failure mechanisms to prevent or minimise their impact on mine safety and production. In the case of monitoring rock mass with intelligent rock bolts, further investigation and data collection are necessary. Although it will be a lengthy learning process, advances in technology and deformation measurement throughout the entire bolt tendon will lead to better comprehension and potential prediction of failures.

The 'intelligent rock bolt' is an instrumented bolt with different types of sensors (Nöger *et al,* 2021; Fuławka *et al,* 2022). There are many possible additions and combinations of installing sensors, depending on the needs of the specific mining site. Rock bolts could have a deformation monitoring system that tracks the deformation of the bolt in time and reports its capacity and performance to the central unit. This kind of sensor would provide better insight into the rock mass and behaviour of the excavation stability (Varelija and Hartlieb, 2024). The whole concept works in a way that the sensor deforms together with the bolt and the readout unit detects that deformation in the form of a resistance change of the sensor. For that to be possible, the sensor needs to be fixated on the bolt without any decoupling (Figure 1). To date, this system has been tested with expansion shell rock bolts.

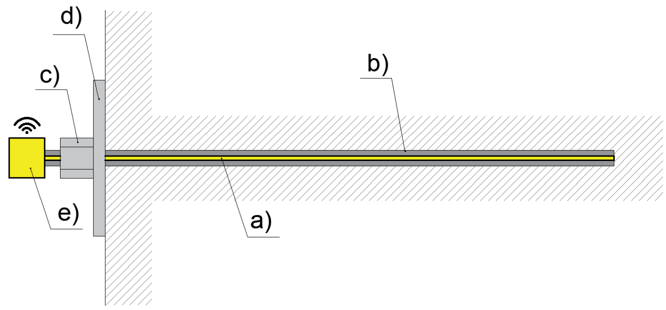


FIG 1 – Intelligent rock bolt components: (a) deformation sensor; (b) rock bolt (steel bar), (c) nut; (d) plate (e) wireless readout unit (collecting and sending data) (after Varelija and Hartlieb, 2024).

The main advantage of this concept is that the sensors are based on low-cost technology, and hence the price per bolt is marginal reducing the economic load/risk of their implementation.

MONITORING DATA ACCUMULATION and DATA STREAM PROCESS

This system has the potential for automation of measurements, identification of overloaded bolts, analysis using pre-developed algorithms, and visualisation of the results. However, the situation is not that simple for interpretation of the results, learning processes, converting information into safety status, and deciding on mitigation or counter measures. This means that measurement is the simplest and most automatable aspect of the entire process. That is something that can be automated, repeated and displayed via suitable Internet of Things (IoT) communication, platforms and related dashboards and evaluation algorithms (Miñón *et al,* 2022). However, the process goes further: an engineer must be involved, someone with expertise and knowledge of the mine, as well as someone who can look at the big picture and make the decision. In this part, an automated algorithm can give recommendations and help the engineer to learn and study the situation, but the decision in the end needs to be made by a human. In this context it is important to note that from the five essential steps identified (measure, analyse, interpret, learn, decide) only the first two can be automated with currently available technologies and knowledge, whereas the subsequent decision-making process still needs to be performed by trained engineers. In the example of intelligent rock bolts that would mean that the automated system can recognise the individual behaviour of bolts as well as the behaviour of clusters of bolts in 4D (time is an essential ingredient in mining). Furthermore, it can analyse how these clusters and areas are related to each other and the mining sequence. However, the ultimate decision whether the mine needs to react or change its process is to be taken by the engineer!

ACKNOWLEDGEMENTS

This paper was prepared within the framework of the illuMINEation project. The project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement no. 869379.

REFERENCES

Fuławka, K, Pytel, W, Szumny, M, Mertuszka, P, Pałac-Walko, B, Hartlieb, P, Jakic, M and Noeger, M, 2022. Prototype of Instrumented Rock Bolt for Continuous Monitoring of Roof Fall Hazard in Deep Underground Mines, *Sensors (Basel, Switzerland)*, 23(1). https://doi.org/10.3390/s23010154

Kolapo, P, Onifade, M and Praise, O A, 2022. An Overview of the Use of Rockbolts as Support Tools in Mining Operations, *Geotechnical and Geological Engineering,* 40(4):1637–1661. https://doi.org/10.1007/s10706-021-02005-5

Miñón, R, Diaz-de-Arcaya, J, Torre-Bastida, A I and Hartlieb, P, 2022. Pangea: An MLOps Tool for Automatically Generating Infrastructure and Deploying Analytic Pipelines in Edge, Fog and Cloud Layers, *Sensors (Basel, Switzerland)*, 22(12). https://doi.org/10.3390/s22124425

Nöger, M, Hartlieb, P, Ladinig, T, Moser, P, Grießer, T and Dendl, D, 2021. The potential of a mine-wide digital rock mass condition monitoring system, in *Proceedings of International Future Mining Conference 2021*, 3 p (The Australasian Institute of Mining and Metallurgy: Melbourne).

Varelija, M and Hartlieb, P, 2024. Designing Intelligent Rock Support Systems to Detect Gravity-Driven Wedges, *Rock Mech Rock Eng.* https://doi.org/10.1007/s00603-024-04039-6

Annual survey of technological transformation in the mining and minerals exploration industry, 2023

W J Haylock[1] and K Wasiel[2]

1. Managing Director, PX4 Software, Brisbane Qld 4000. Email: bill.haylock@px4software.com
2. Senior Business Analyst, PX4 Software, Brisbane Qld 4000.
   Email: kat.wasiel@px4software.com

ABSTRACT

PX4 Software Pty Ltd is a Brisbane-based company, which specialises in providing tenement management software to mining and exploration teams operating in Australia and several international jurisdictions, including the United States, Africa, and Canada. Whilst the company is experiencing substantial growth due to a demand from both the minerals and mining technology sector, there is a crucial gap in the market for critical minerals, which will be required to achieve the net-zero emissions goal set by the Paris Agreement for 2050. To help understand and address the technology gap identified by the unprecedented demand, PX4 Software undertook the Annual Survey of Technological Transformation in the Exploration Industry. This survey involved interviews with 12 very distinguished subject matter experts in the fields of Geoscience and Geology from across the globe.

From this survey, we have defined eight major categories of exploration technologies. Notably, the most transformative of these technologies over the past 65 years falls into the Geophysical Methodology category, specifically focusing on image and signal processing of both airborne and downhole data. Advances in computing power during this period have significantly improved data processing quality, enhancing orebody modelling, and targeting. This has had a profound impact on the industry.

Moreover, the survey reveals that future transformative technologies are expected to centre on the automation of existing processes through AI and Machine Learning techniques. This is expected to help facilitate the identification of critical mineral systems and thus enable the exploration industry to make more informed decisions based on data analysis using Machine Learning and AI.

The survey also brought to light two critical requirements in meeting the demand for critical minerals. Firstly, there is a pressing need for technology capable of locating mineral systems at depths as great as 2 km, with a particular emphasis on copper. Secondly, a consistent flow of funding towards the junior exploration companies' activities is essential. The boom or bust scenario is not providing long-term consistency in exploration efforts and activities.

While larger mining companies, such as BHP and Rio Tinto, have implemented robust funding programs, and governments have supported critical minerals initiatives, the whole exploration industry has historically struggled to keep pace with technological innovation. This lag is attributed to the industry's complex regulatory environment and market fragmentation and a follower mentality.

To achieve the emission reductions targets by 2050, as outlined in the Paris Agreement, we recommend that exploration and mining companies seek partnerships with major technology firms to leverage their expertise in developing technological solutions and to ensure a more consistent flow of funding. As technology continues to advance and its benefits become more apparent, the mining industry is poised to increase investment in and adoption of cutting-edge technologies.

INTRODUCTION

This report presents the outcomes of PX4's annual exploration survey, which focuses on the historical and anticipated technological transformation within the mineral exploration industry. The survey serves as a comprehensive review of technological developments, their impact on the industry, and the key technologies expected to drive future transformations. The survey was conducted in early 2023 and involved prominent Australian Exploration Geologists and Geophysicists with extensive careers in the field.

The participants in this survey represent a wealth of experience, individually spanning 29 to 53 years in the industry. In total 467 years of collective experience. This exceptional depth of knowledge enriches the findings of the survey and provides valuable insights into the industry's technological evolution.

METHODOLOGY

The survey involved the presentation of four primary questions to the participants:

1. What were the cutting-edge technologies in the field when you began your career?
2. How have the cutting-edge technologies evolved over the course of your career?
3. What technologies do you foresee as the harbinger of transformation in the future?
4. If you could wave a magic wand to address a technology-related challenge in the industry, what would it be?

A fifth question, 'Have you experienced resistance or barriers to adopting and embracing technologies?' was also included to assess the hurdles to technology adoption.

A total of 12 comprehensive survey responses were collected, encompassing a wide array of technology types used globally, with a primary focus on Australia, Nevada, Alaska, and Canada. These regions are prominent in the field of mineral exploration. The responses were categorised and analysed, leading to the identification of transformative technologies from the past, insights into expected impacts in the future, and the articulation of a wish list for future technological developments.

The survey delved into the challenges and resistance encountered in adopting new technologies. This aspect is of critical importance, as it plays a pivotal role in shaping the industry's ability to embrace innovation and navigate change. It also addresses the societal costs associated with resisting technological evolution.

WHAT TECHNOLOGIES EXISTED WHEN?

The report includes a detailed timeline spanning the decades from the 1960s to the 1990s, highlighting the emergence and evolution of an array of technologies within the mineral exploration industry. This timeline vividly illustrates the dynamic nature of the mining and exploration sector, where both technological advancements and industry needs drive each other forward.

The responses from this period have now been organised into specific categories that mirror the operational environment of the exploration industry, encompassing:

1. Data Storage and Analysis (Computing Power).
2. Administration and Management.
3. Land Access.
4. Geological Mapping.
5. Physical Sampling.
6. Geophysical Methodology.
7. Geochemical Methodology.
8. Laboratory Analysis.

Whilst there is a huge variability in the number of technology types included within this year's survey results, it does however provide a comprehensive analysis of the most transformative technologies to date and a detailed historical timeline.

FIG 1 – Historical timeline of exploration technologies.

During the participants' early careers, spanning the 1960s and 1970s, significant technological advances were observed. These were further enhanced in the 1980s and included the introduction of computers, Geographic Information Systems (GIS), and 3D modelling software. These innovations revolutionised the industry by enhancing efficiency, streamlining workflows, and facilitating resource planning.

Importantly, the responses underscored that the digital database for sampling and 3D modelling, coupled with satellite imagery, delivered substantial advancements in exploration insights and data analysis efficiency. The adoption of computers and GIS led to more straightforward, cost-effective resource planning and the assessment of mineral potential at both local and regional scales. Furthermore, the application of seismic technologies for capturing downhole geophysical data was transformative, setting the stage for the digitisation of the exploration, mining, and metals industry.

THE MOST TRANSFORMATIVE TECHNOLOGY OVER THE PAST 65 YEARS

The survey posed a pivotal question: 'What are the most transformative technologies you have seen over the course of your career?' This inquiry traversed a 65-year period, capturing the trajectory of technological evolution in the exploration industry.

The response to this question spotlighted 30 technologies that have fundamentally transformed the industry. From these, the most transformative technologies (highlighted in orange in Figure 2) over the last 65 years were image and signal processing technologies of both airborne and downhole data, found in the Geophysical Methodology category.

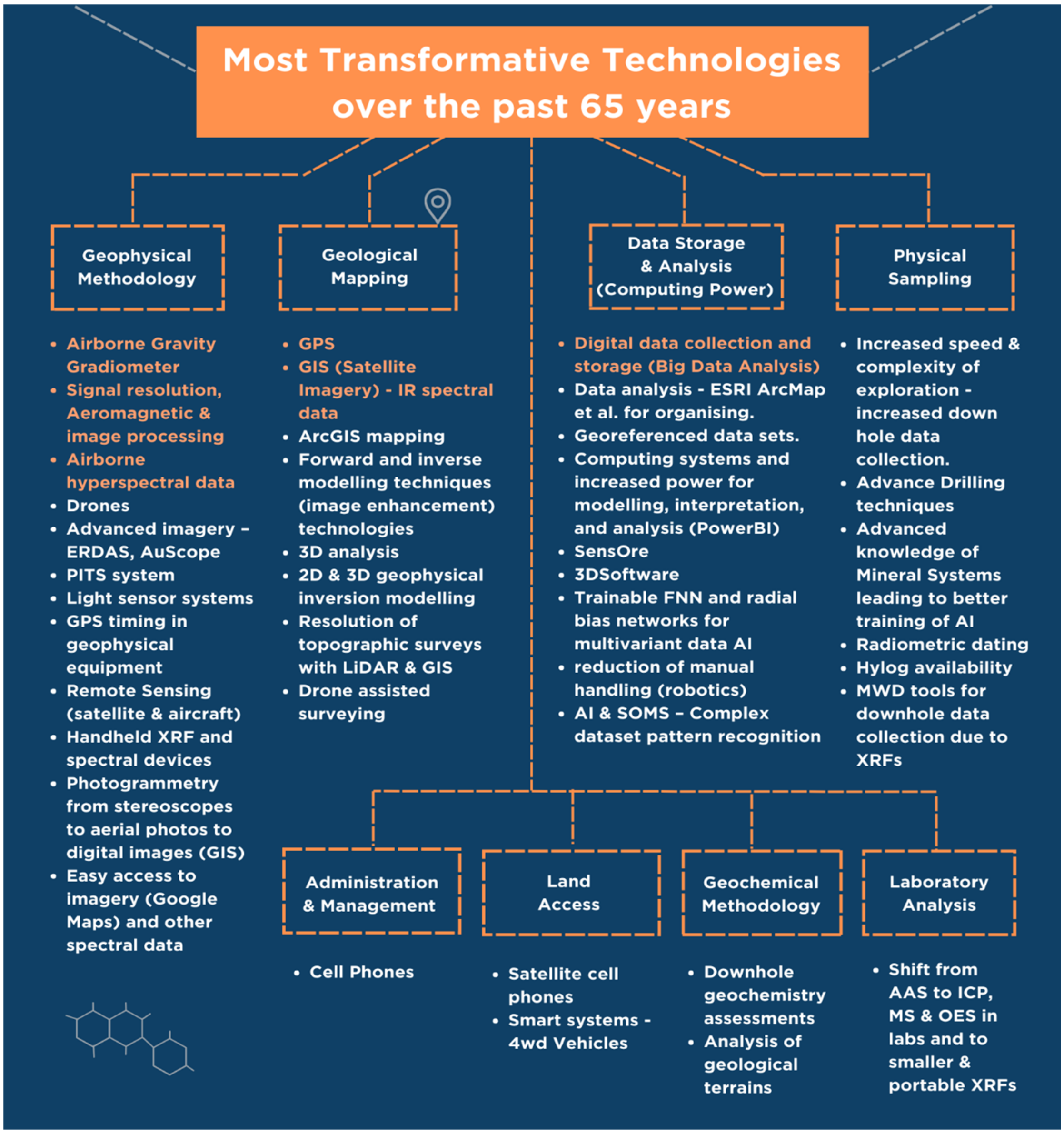


FIG 2 – Most transformative exploration technologies over the past 65 years.

Following closely behind were GPS and GIS capabilities including satellite imagery, found within the Geological Mapping category. And finally, Big Data Collection and Analysis, found within the Data Storage and Analysis category, rounded up the most transformative technologies from the past 65 years, which was primarily made up of data collected from these top transformative technologies and therefore led to a demand for increased computing power.

Notably, these technologies have profoundly impacted the efficiency, workflow, and resource planning in exploration. Importantly, they paved the way for the digitisation of the mining and metals sector. These technologies encompass a range of advancements and innovations, and our analysis has identified the 30 most transformative among them.

MOST LIKELY TRANSFORMATIVE TECHNOLOGIES OF THE FUTURE

The survey ventured to explore the future, probing the question: 'What do you think are the most likely transformative technologies of the future?' The responses to this question unveiled a compelling vision of the forthcoming technological landscape.

Machine learning and AI, and Data Analytics (highlighted in orange in Figure 3) emerged as the two dominant technologies expected to drive future transformations. Following closely are advances in technologies aimed at defining new mineral systems and are anticipated to play a pivotal role in our future.

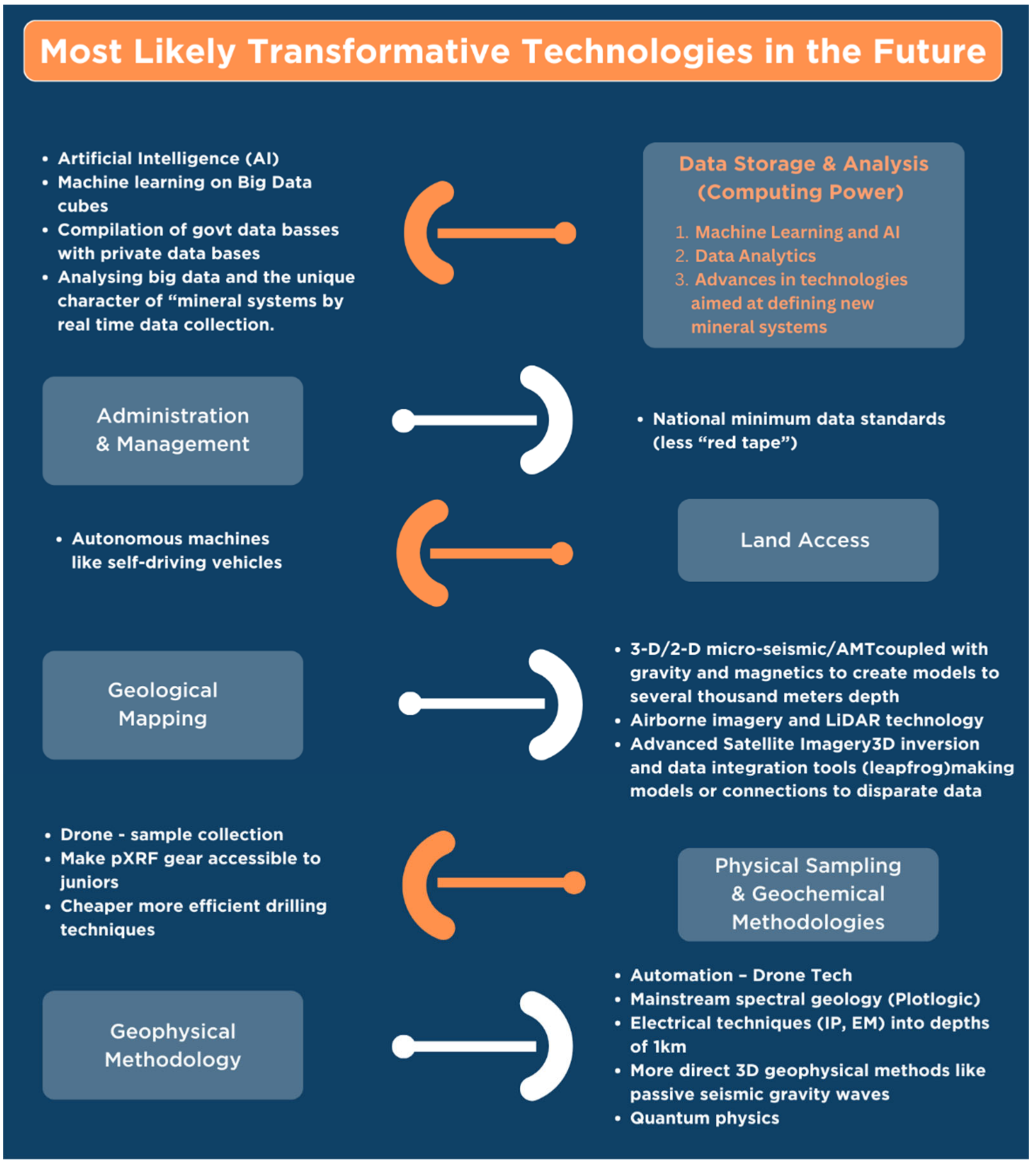


FIG 3 – Most anticipated transformative exploration technologies.

The widespread adoption of technology has generated vast data sets, necessitating advanced or improved technologies, such as Big Data Analytics and AI, which will derive knowledge and value. This is expected to result in significantly improved efficiency in identifying prospects at considerable depths with fewer drilling requirements.

BARRIERS TO ADOPTING AND EMBRACING TECHNOLOGIES

The participants also highlighted potential barriers to adoption, including a lack of understanding about technology and concerns about job displacement. Addressing these challenges will be essential to realise the full potential of future transformative technologies.

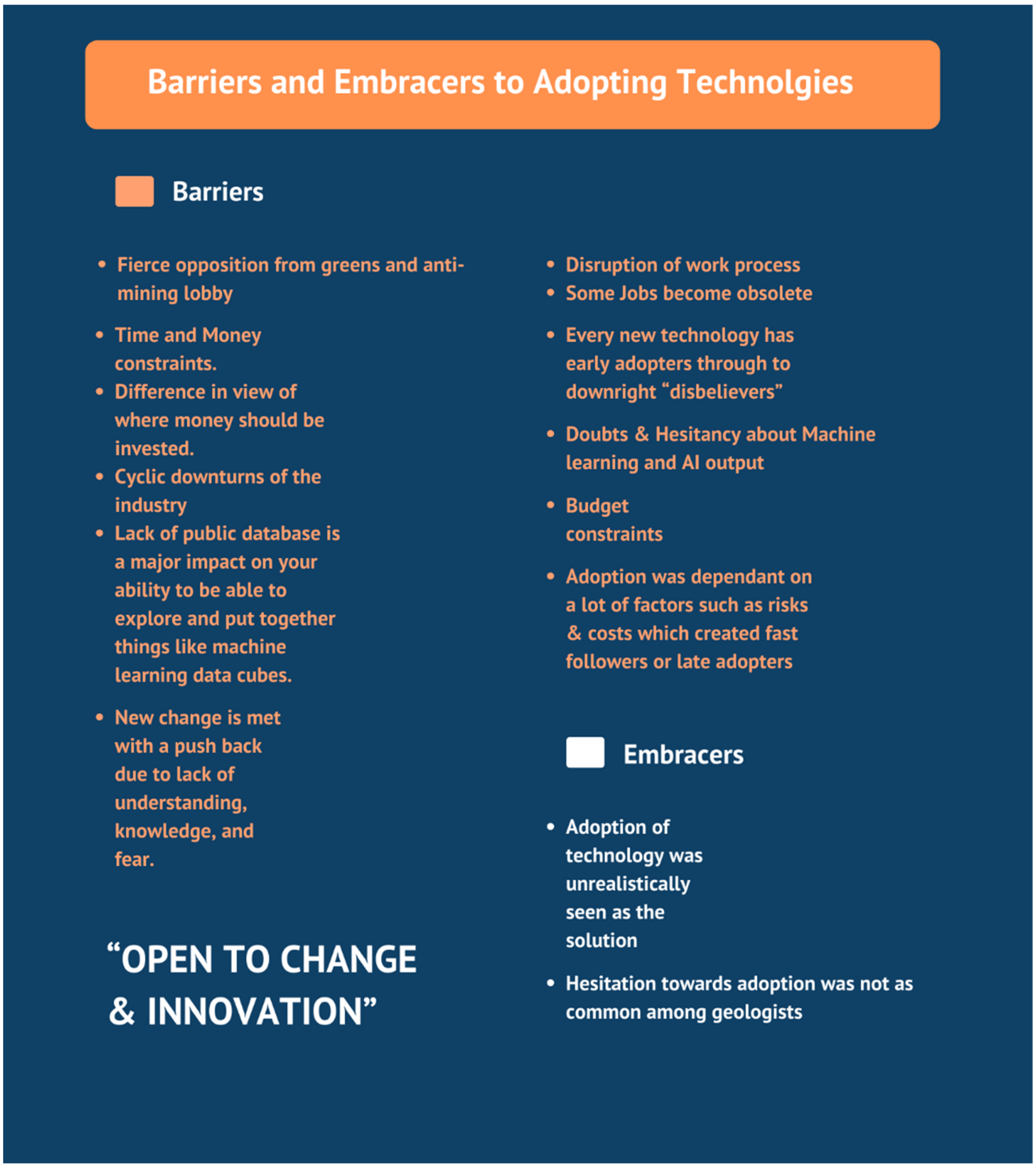


FIG 4 – Technological barriers.

TECHNOLOGICAL WISH FOR THE FUTURE

The survey posed an intriguing question: 'If you had one wish that would fix a technology problem in your industry, what would it be?' This question allowed the participants to express their wishes and frustrations, and with a cumulative experience of 467 years at their disposal, our legislators need to take heed.

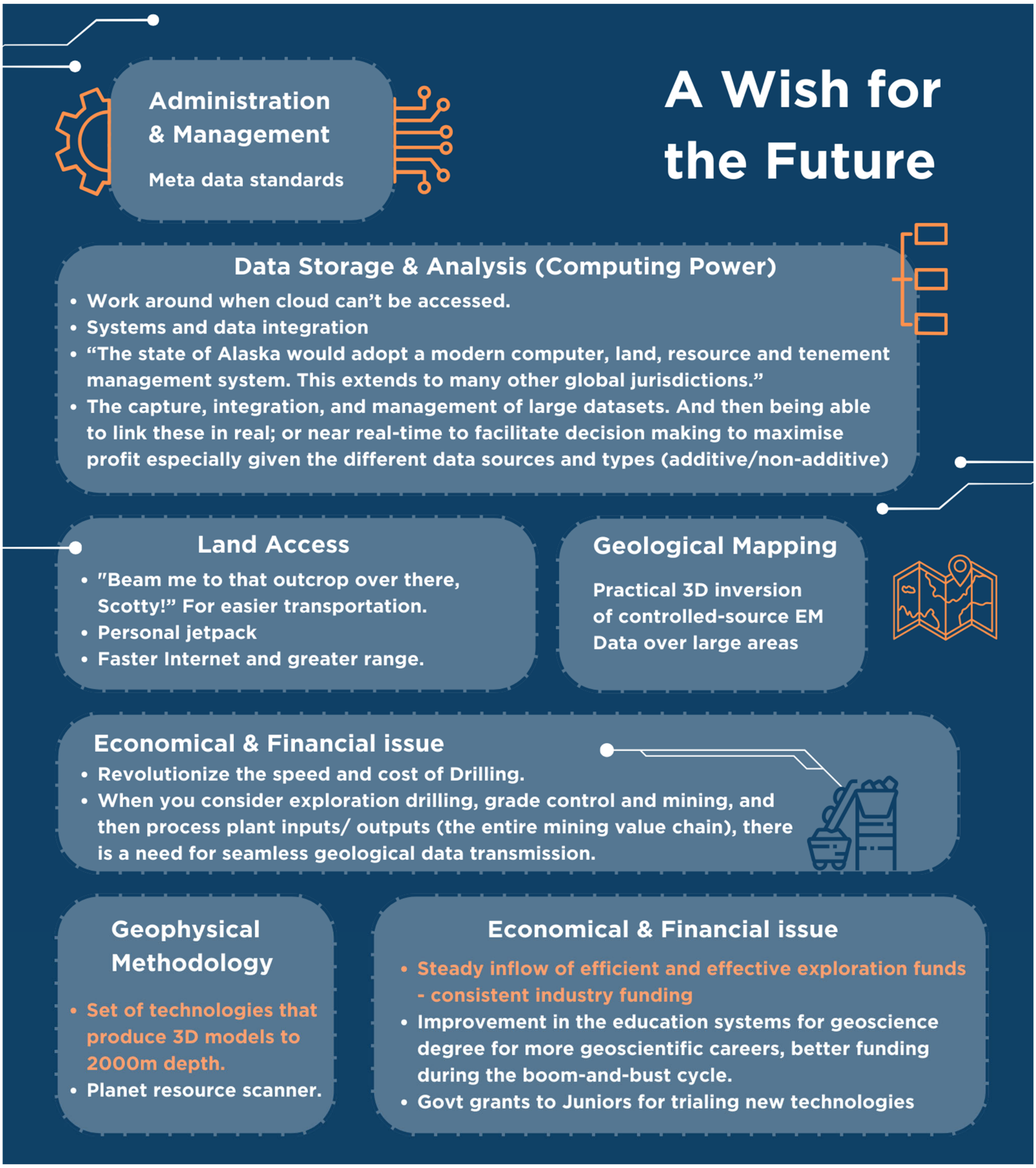


FIG 5 – Technological wish for the future.

Two main themes emerged from this question, echoing the fundamental requirements highlighted in the Executive Summary:

1. The need for technology capable of locating mineral systems at significant depths, particularly focusing on copper. See Appendix.
2. The imperative for a consistent and substantial flow of funding for the junior exploration efforts and activities. They are after all the most significant of our exploration efforts.

The urgency of these requirements cannot be overstated, as they are intrinsically linked to the industry's ability to meet the global demand for critical minerals and adhere to the Paris Agreement's goals.

CONCLUSION

In summary, the pursuit of critical mineral systems and mineral systems in general, at significant depths is not merely an industry mandate; it is a global imperative. To achieve the net-zero emissions target, the mining industry must spearhead innovation, embrace change, and meet global expectations in line with the Paris Agreement.

The digitisation of mineral exploration is not a choice; it is a mandate for progress. It is the solution to our problems and as such needs to be embraced and perhaps loved. It promises to align the most attractive mining jurisdictions with the aspirations of investors and the global community. While new technologies hold the potential to transform the industry, they do scare many practitioners in their varied roles. However, these technologies must be met with open arms and a commitment to overcome the challenges.

The time has come for bold action. Government incentives and corporate programs, while commendable, are no longer sufficient to meet the massive demands for all minerals. We must rally the support of major technology giants that have their roots in the mining industry. Together, we can champion the transformative technologies of the past 65 years and embrace the most promising innovations of the future.

In doing so, we can bring 3D models of mineral systems to life, even at depths of up to 2 km, revolutionising the speed, cost, and automation of drilling. This, in turn, will empower junior mining companies to pioneer exploration technologies and big data analysis techniques, driven by ever-increasing computing power.

The path ahead is illuminated by innovation, guided by the wisdom of industry veterans, and powered by the courage to embrace transformative technologies. It is a journey that holds the promise of meeting the net-zero emissions.

The future is bright, and it beckons us to seize it with both hands.

ACKNOWLEDGEMENTS

We kindly thank the following people whom were interviewed by Bill Haylock and Toby Carrigan (from PX4 Software Pty Ltd) in November of 2022: G Beischer, A Browne, T Crabb, M Dugmore, G Edser, P Harmon, D Hedderly-Smith, D Hedger, D Hope, J Main, S McInnes, D Szumigala and T Whiting.

REFERENCE

Minerals Council of Australia (MCA), 2022. *Commodity Demand Outlook 2030.* Available from: <https://minerals.org.au/wp-content/uploads/2022/12/Commodity-Outlook-2030.pdf> [Accessed: 1 November 2023].

APPENDIX

A comparison between Figures 6 and 7, highlights the requirement of more copper mine development to meet global demand which begins by finding the mineral system at depths of up to 2 km.

'We need the USS Enterprise's cool planet resource scanner used by Dr Spock!'

– Darryn Hedger, 2023.

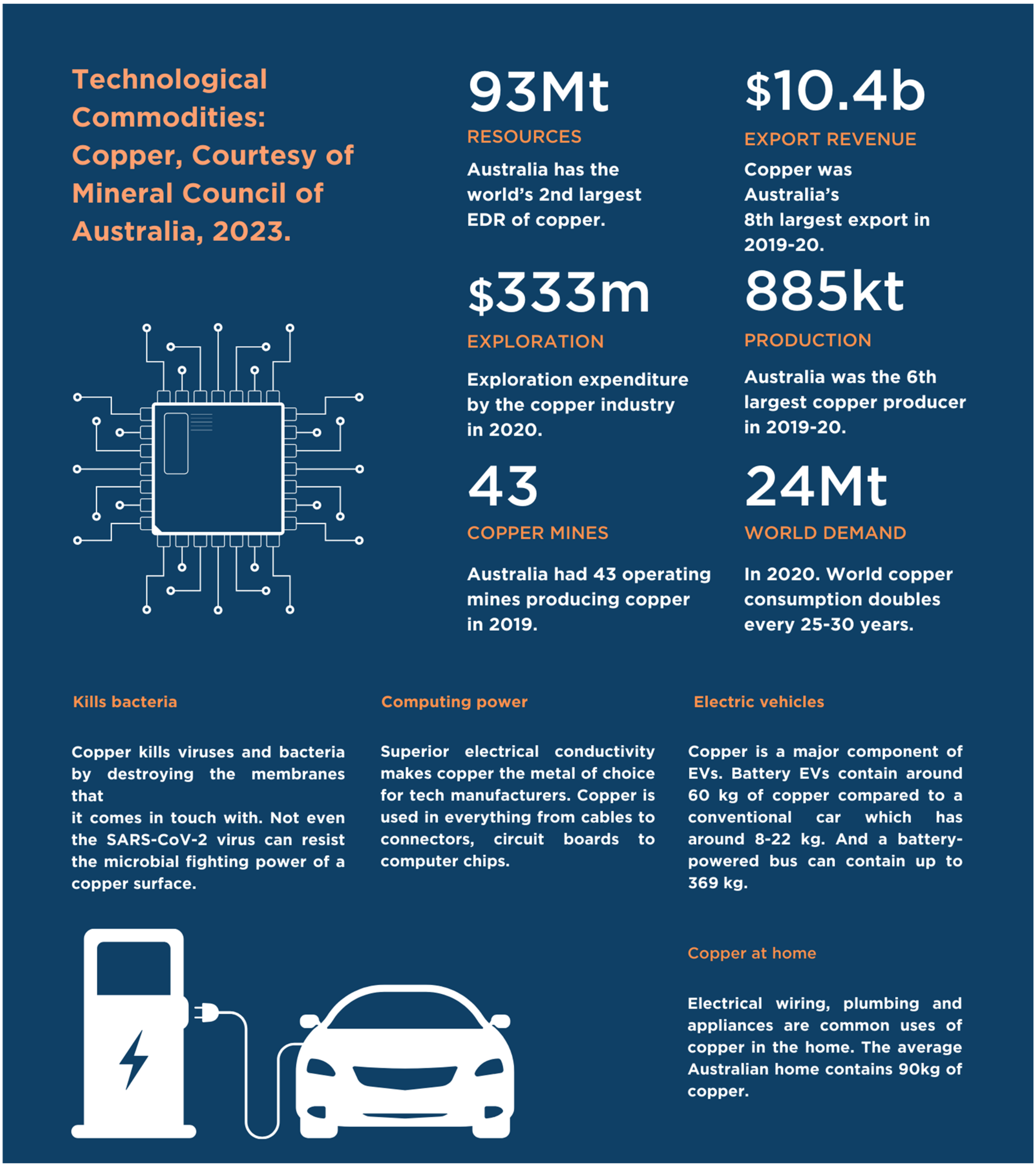


FIG 6 – Technological commodities: copper, courtesy of MCA (2022).

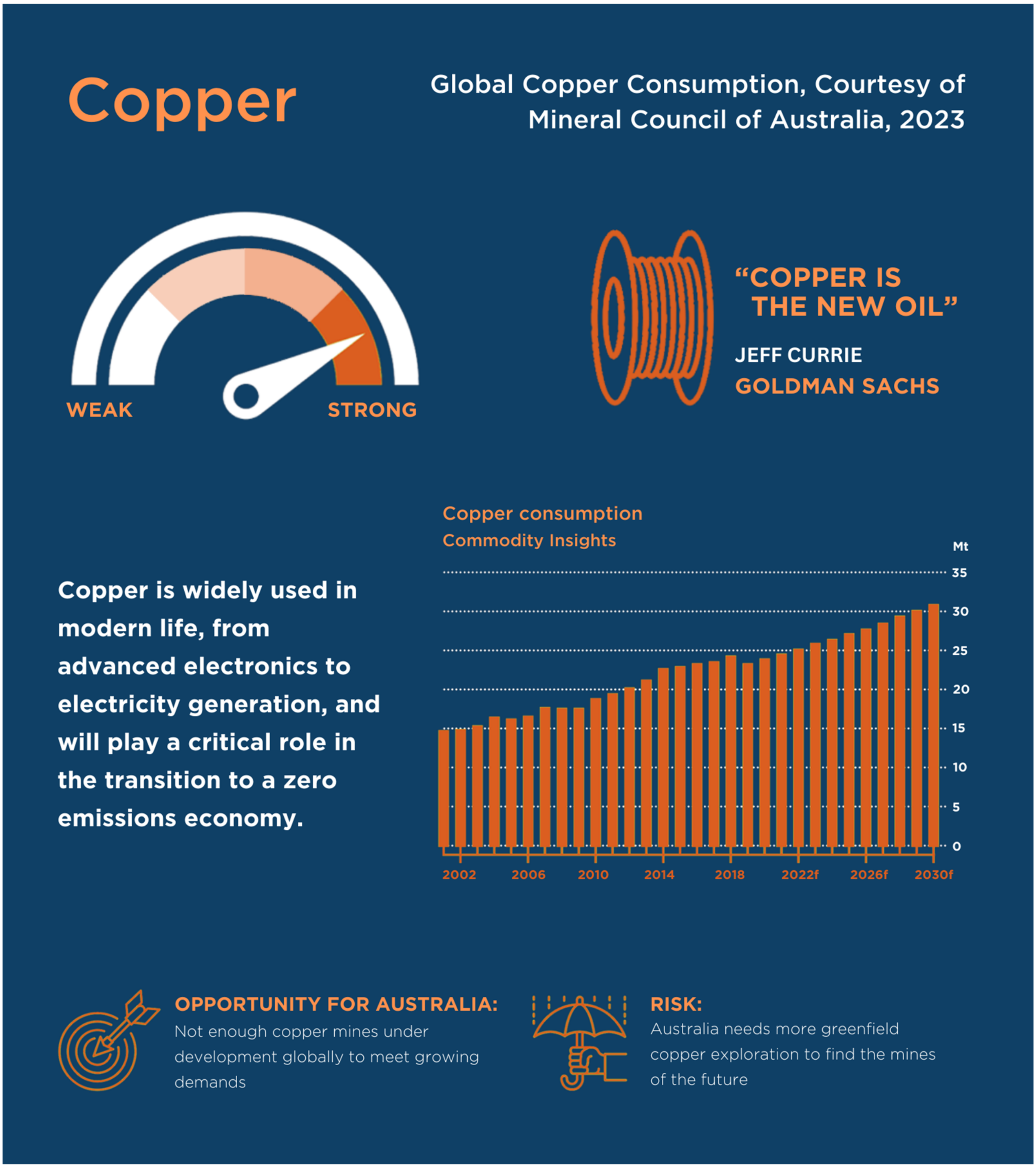


FIG 7 – Global copper consumption, courtesy of MCA (2022).

Reducing the environmental and economic cost of metal extraction by optimal blast design

L Julian[1], W Hunt[2], R Pratama[3], D La Rosa[4] and A Tsang[5]

1. Principal Engineer, Orica, Windsor Qld 4030. Email: lee.julian@orica.com
2. Senior Consultant – Technology, Orica, Centennial CO 80112, USA. Email: will.hunt@orica.com
3. Master's Student, Colorado School of Mines, Golden CO 80401, USA. Email: ryanyogapratama@mines.edu
4. Manager – Technology, Orica, Windsor Qld 4030. Email: david.larosa@orica.com
5. Product Manager – Technology, Orica, Melbourne Vic 3002. Email: alfred.tsang@orica.com

ABSTRACT

Mineral extraction is facing the twin challenges of finite resources and increasing environmental and economic costs. Society's growth is matched by an increase in demand for the earth's resources. It is incumbent on us as contemporary mining professionals to promote and facilitate ethical and efficient practices. Technological developments have and will continue to allow a decrease in viable cut-off grades, creating new economic opportunities from deposits that were previously uneconomic. Mining low-grade deposits however, even with perfect recoveries, will have a significant environmental cost for the metal won. The greatest opportunity to increase metal with the least environmental cost is to increase the metal yield from existing mines.

The determination of mining polygons is a critical juncture where rock is typically subjected to the binary grading of either ore or waste. This is undertaken using a number of factors, such as the mining equipment being used and the recovery in the processing plant. Traditionally, mining polygons were generated on the *in situ* grade control model. This ignores the complex differential blast dynamics that occur during blasting. Two opportunities exist to improve metal yields: optimise the blast design to achieve the post-blast muck pile that will support the greatest outcome; and generate optimised polygons on the post-blast muck pile.

A data set from a Canadian Gold deposit is used to demonstrate the potential benefit of iterative blast movement modelling and grade control polygon optimisation on metal yield. The impact of blasting on the total recoverable metal is presented, highlighting blast design as a critical process in the mining value chain.

INTRODUCTION

The importance of mitigating the effects of blast movement has been well-understood for decades. In the early 1980s, ICI (pre-cursor to Orica) and others began working to build blast movement models (heave models) with Sandia National Laboratories (Preece and Taylor, 1990; Preece, Chung and Tidman, 1998), with the hope of creating operational models that could mimic blasting and create representative muck piles (Yang and Kavetsky, 1990). These early models lacked computer power, leading to extremely long processing times and over-simplified representations of the blast (Hunt, 2023).

While efforts to create operationally viable heave models continued, less-computationally heavy methods were used to mitigate the effects of blast movement by shifting grade control polygon nodes two-dimensionally (Taylor, 1995). In this process, the *in situ* attributes of the polygons were typically assigned to the post-blast polygon locations, even though the tonnage and geochemical attributes changed (Isaaks, 2019). The assumption that the original polygons, now shifted, still contained the same tonnes and attributes is a result of the difficulty in solving two problems:

1. A post-blast grade control model is required to inform the attributes of the overlying polygon.
2. Reconciliation and planning are much simpler if the quantity and composition of planned polygons remain unchanged.

In early 2019, a reactive blast movement model and polygon optimising program was created (Reactive Model) which required a survey of the post-blast muck pile surface to create a post-blast grade control block model (Hunt and La Rosa, 2019a, 2019b). This computer program effectively solved the first problem by properly coding grade control polygons by their contents but not the second problem of reconciliation and planning.

To illustrate the potential opportunity with reconciliation and planning, a large study of over 150 blasts was conducted with the Reactive Model that investigated the relationship between pre-blast value possible and post-blast value possible (Figure 1). In this analysis, 'value' is equated with 'profit'. The quantity of ore loss and dilution is irrelevant, as value and profit are affected by ore loss and dilution (Hunt, 2023).

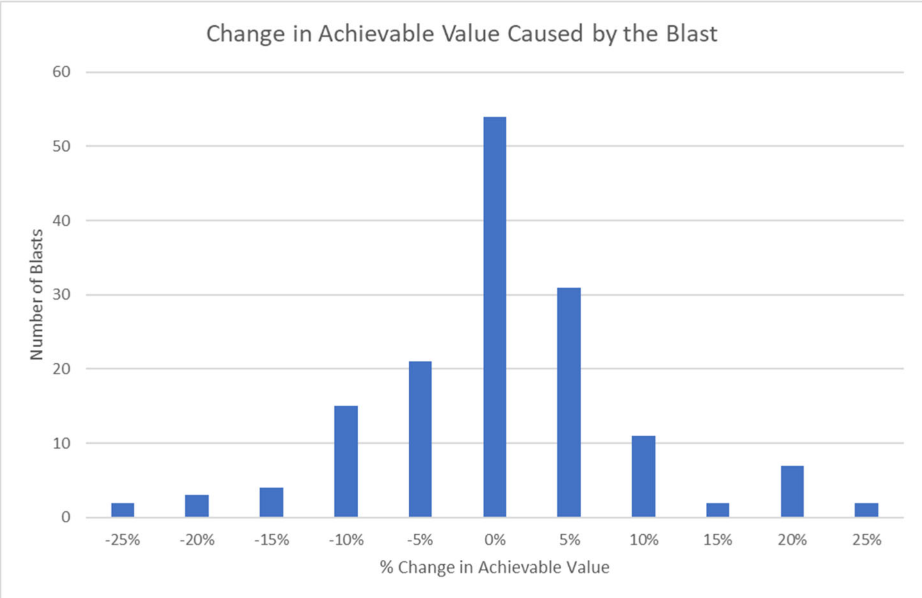


FIG 1 – Change in value achievable caused by blasts (Hunt, 2023).

To eliminate bias caused by human interpretation, the scenarios were calculated using the exact same polygon optimisation algorithms. The results indicated that some blasts increased the possible value, while some detracted from value, with the mean resulting in no change. The blast can change the value achievable, but Planners, Blasters, and Geologists must know what *will* happen *before* it happens if they have any hope in optimising or planning for outcomes.

Orica added predictive capabilities to the Reactive Model in 2023 to create a 'Predictive Model'. This program uses previously gathered data from the mine to calibrate itself and produce a post-blast heave model without the need for a post-blast muck pile survey. The Predictive Model has been implemented at many mines globally, but most operations have used the program for the sole purpose of eliminating the need for a post-blast survey of the muck pile, which is a requirement of the reactive model. Few mines have used the program to evaluate possible blast designs before the blasts are initiated, despite the clear utility in doing so. Key questions needed answering to resolve this issue:

- Why are mines not using the program for planning?
- Is the potential value provided by blast design insignificant?
- Is the task too cumbersome?
- Are the results close enough to the *in situ* planned outcomes that post-blast planning is not helpful?

Once these questions are answered, the results may lead to another very important question and a common barrier to innovation:

- Are the mine's systems too rigid to allow for new methods of planning?

HYPOTHESIS

To answer the questions posed above, an experiment was conducted whereby blasts would be modelled with different timing designs. The pre-blast optimised polygons were compared with the post-blast optimised polygons for change in value caused by the blast design. The value achievable in the post-blast optimised polygons were compared with the *in situ* polygons in these situations:

- Original blast designs.
- The blast design with the highest value.
- The blast design with the lowest value.

The hypothesis was that the value contained inside of the optimised post-blast polygons possible in the original blast designs would fall somewhere between the value possible in the best and worst blast designs, leaving some possible opportunity for value to be created or saved through predictive blast design modelling.

Effects of different timing designs

Timing has a direct impact on the shape of the post-blast muck pile, shown in Figure 2. Since timing is responsible for the direction of movement, changing the timing will change the shape of the ore/waste contacts in the post-blast muck pile and thereby change the optimised grade control polygons (Hunt and La Rosa, 2019b).

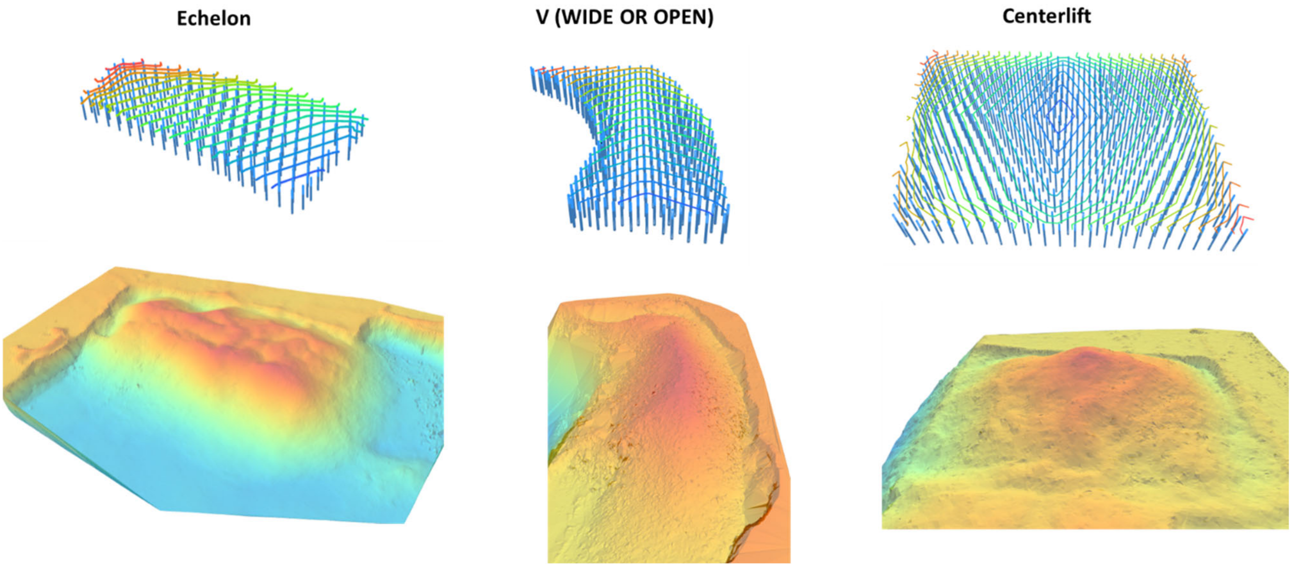


FIG 2 – Timing creates different muck pile shapes.

The authors of this study changed the initiation point and angle of the timing contours only, resulting in different blast timings for predictive evaluation. Blast energy and burden relief were not changed as these are required to achieve specific design outcomes, such as fragmentation, vibration and muck pile looseness.

Effects of mining direction and angle of mining

The effect of mining direction on value depends heavily on the geology. For example, the effects of mining direction and method will be significantly greater on a narrow vein deposit than on a widely disseminated porphyry deposit. The polygons created to delineate the structures in a narrow vein could completely miss the target if digging direction is not considered. Figure 3 shows the effect of the dip angle and direction of attack on a narrow vein orebody where a 60° mining face angle was assumed (Hunt and La Rosa, 2019a).

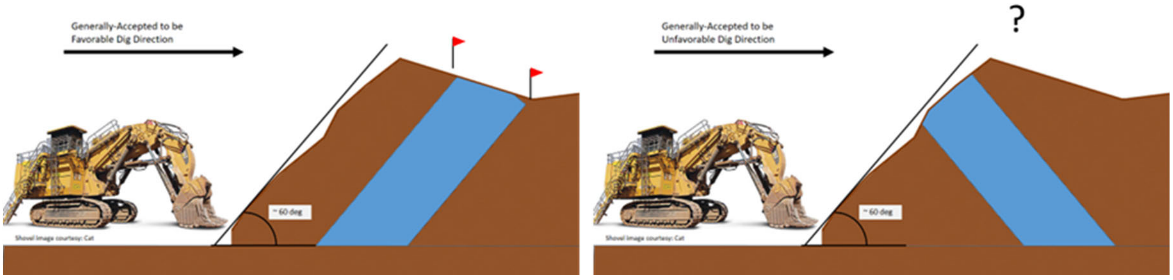


FIG 3 – Mining direction and narrow veins (Hunt and La Rosa, 2019a).

Ruling out any effect from the selected mining direction is difficult, as the mine may choose to attack a muck pile from a different direction if a different blast timing is used. For this reason, four mining directions were analysed with each blast design. The mine had determined that their working face varies between 70–75°, depending on whether they would mine with a single or multi-flitch method on that blast. So, the same angle used by the mine was assumed regardless of the mining direction.

EXPERIMENT

The following section describes the experiment and analysis by which the authors attempted to validate or disprove the hypothesis. It involves comparisons between *in situ* and post-blast optimised polygons in the original blast designed, and changing the timing in the blasts to see how the post-blast value achievable is affected.

Inputs

A data set consisting of 33 recent blasts from a single mine was provided by a Canadian gold customer. Each blast contained the following data:

- pre-blast topography
- post-blast topography
- hole loading, layouts and timing
- grade control block model with attributes and density
- material classification rules and routing
- recovery and costs.

Assumptions

The following assumptions were made to conduct the experiments described. A full discussion on model accuracy and the quality control/quality assurance (QA/QC) method used is provided in the section Discussion of Error.

- All $ values are in USD.
- The grade control model provided is 100 per cent accurate.
- The topo surveys provided are accurate, apart from slight areas that required 'cleaning', such as in Figure 7.
- The predicted post-blast model is accurate.
- The blasthole loading provided is accurate.
- Mining face angle varies between 70–75°.
- Bench height is 14.5 m.
- The number of flitches, or horizontal slices, was kept consistent:
    - If the blast was designed to be excavated with a single pass, a single set of optimised polygons was created for each mining direction.

- If the blast was designed to be mined in two passes, polygons on each flitch were created and the mining direction was assumed to be consistent in both flitches.

- MMU, or 'Minimum Mining Unit' is 20 × 20 m.
- Breakeven cut-off grade is 0.5 g/t Au.
- Au price is USD2037/troy ounce.
- Mill recovery is 90 per cent.
- Net ore and mining cost ('Cost') is USD29.47/t.
- Value = $Metal recovered – (Cost × tonnes).
- Polygon optimiser is providing the best possible polygons for value in each iteration.
- Mining direction and mining face angle are consistent through the entire blast volume.
- There are infinite 'possible' blast designs. This study assumes three blast designs were possible: a centrelift, an echelon, and an open V.
- The time between rows in each blast design is consistent with the original blast design.
- *In situ* mining, even though impossible to achieve, is assumed during *in situ* polygon optimisation for the purposes of measuring the effect of the blast on value possible.

Exclusions

Many things contribute to the overall value of a blast, including explosive costs, fragmentation, and digability. Additionally, blasters have considerations over and above grade control, such as safety, vibration, and wall control. This study only considers grade control 'value', or 'profit' in the analysis. The other items listed should be considered in any blast design and are certainly value-drivers that should be considered in an overall blast design.

METHOD

In each blast, the following process was followed:

- Open and QA/QC blast.
- Create post polygons using the original blast timing:
  - Four possible mining directions (N, S, E, W).
- Make new initiation timing 1.
- Create post polygons using the blast timing 1:
  - Four possible mining directions (N, S, E, W).
- Make new initiation timing 2.
- Create post polygons using the blast timing 2:
  - Four possible mining directions (N, S, E, W).

The result is three different muck piles, each resulting from a different blast design timing (Figure 4).

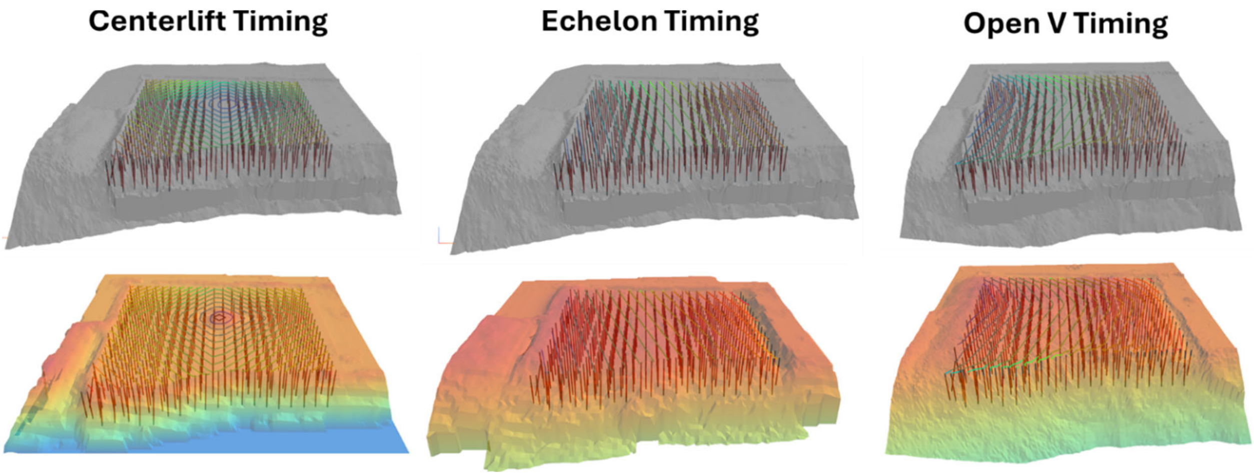


FIG 4 – Different blast timing for the same blast design.

Each post-blast muck pile contains a post-blast model. The grade control polygon optimiser in the Predictive Model was used to create four sets of optimised polygons on the *in situ* model, then four sets of polygons on the post-blast model.

Once the data had been gathered and processed, the results were exported into a spreadsheet. Results from all blasts were combined into a single spreadsheet to enable simple analysis. The post-blast polygons with the highest value were compared to the *in situ* polygons in the same mining direction, thus removing the effect of mining direction on the outcomes.

DISCUSSION OF ERROR / QA/QC

In addition to the normal QA/QC process used during operation of the Predicted Model, other methods were developed to determine if the predictions were accurate enough for use in this study. Certainly, the results of this analysis depend heavily on the accuracy of the predictive simulation and creation of the post-blast grade control block model. It is beyond the scope of this paper to prove the accuracy of the post-blast grade control block model. Several customers of the Reactive Model, which uses the same process for post-blast block model creation as the Predictive Model, have performed independent analysis to determine the accuracy of the post-blast model methodology, including batch testing, grab sampling (not advised), and bulk reconciliation over time. Some of those results have been made available to the public (Hall and Hunt, 2019; Poupeau, Hunt and La Rosa, 2019). It is assumed that the method used by the program to move the *in situ* grade control model into a post-blast grade control model is accurate.

Three QA/QC metrics were used to determine if the Predicted Models were suitable for use.

1. Vertical heave.
2. Simulated replay of the blast.
3. Metal and tonnage balance between the pre and post-blast models.

The QA/QC process for each blast in this study started with a real post-blast topo survey that formed as a result of the original blast design. The design was simulated with the Predictive Model to see if the post-blast simulated topo matched the actual post-blast topo. The first metric used is a comparison of vertical height between the predicted post-blast muck pile and the actual post-blast muck pile. The goal for simulation accuracy during calibration for normal use is <1.0 m or less, which is believed to be an acceptable error. In this study, the average vertical variance is the 33 blasts used is 0.65 m with standard deviation of 0.2 m. All blasts passed the criteria of <1.0 m of variance, shown in Figure 5.

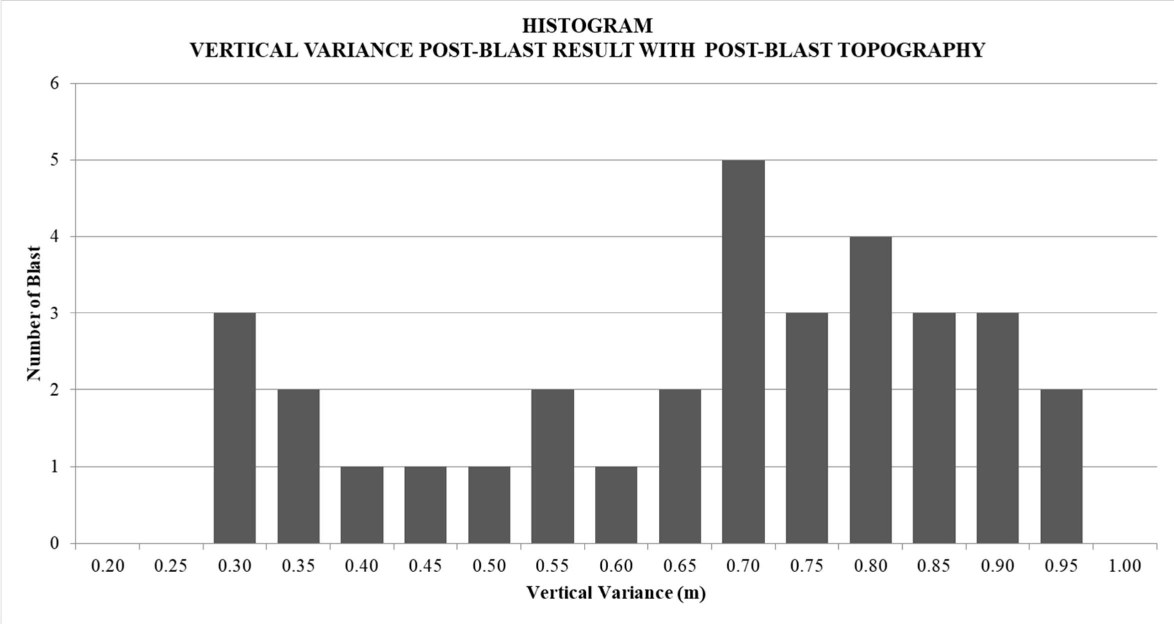


FIG 5 – Histogram of vertical variance between simulated and real topographies.

Another metric, but one much more difficult to quantify, is the visual accuracy of the simulated throw. The Predictive Model creates a graphical video of the blast, including the throw of the rock. In this study, every simulation was viewed to ensure nothing extraordinary was observed, which would indicate a possible error in inputs or outputs. For example, Figure 6 is a pre-blast topo survey that included a drill and vehicle. Before processing, those items were removed from the topo using a smoothing tool inside of the Predictive Model. If those items had not been removed, the playback video would have shown odd behaviour in that region. All blast simulations passed this visual inspection.

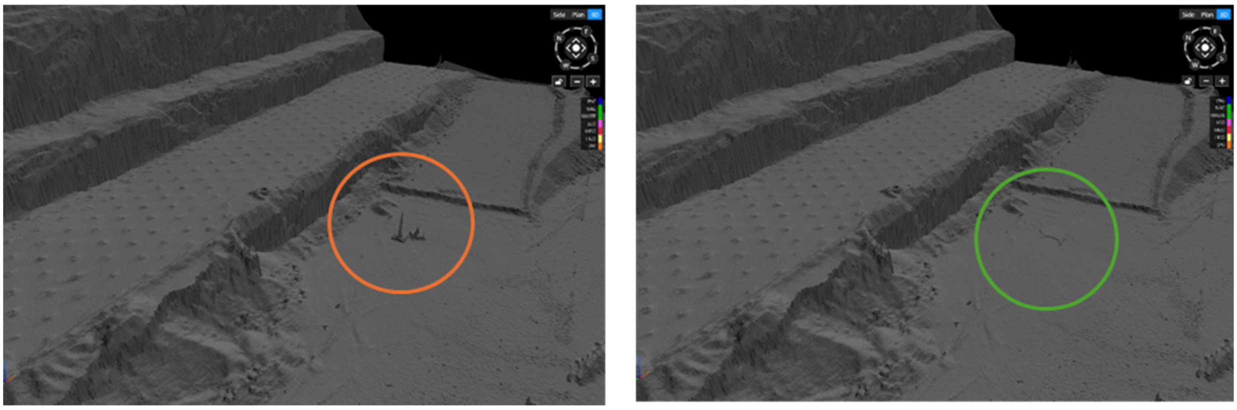


FIG 6 – Removing equipment from the topographical survey.

The last QA/QC was the comparison between pre and post tonnage and metal, or metal balance. For the simulation to be accurate, metal and tonnes cannot be created or destroyed. While this concept seems simple, the practical application is much more difficult to achieve, and many algorithms are working inside of the Predictive Model to ensure that metal and tonnes are logically placed and balanced. This indicator is extremely important when performing sensitive analysis. All blasts passed the metal balance criteria with 100 per cent metal and tonnes retained.

All blasts used in this study passed the three QA/QC checks and were deemed acceptable to use in this study.

RESULTS

The following section detail the comparisons made and the resulting outcomes. In each case the assumed mining direction was consistent pre and post-blast.

Original blast designs

The original blast designs resulted in real post-blast muck piles, not simulated predictions. An analysis was performed comparing the *in situ* optimised grade control polygons to the post-blast optimised grade control polygons in every blast. This helps to understand the impact that the original blast design had on grade control value achievable.

In five of the 33 blasts, the potential value in the grade control polygons was lower post-blast, meaning those blasts reduced the value possible. In the remaining blasts, the value increased. The value differences range from a loss of $143 000 to a gain of $392 000 in a single blast with an average gain of $104 000. The total impact to grade control value was an increase of $3.45 M in the 33 blasts analysed (Figure 7 and Table 1).

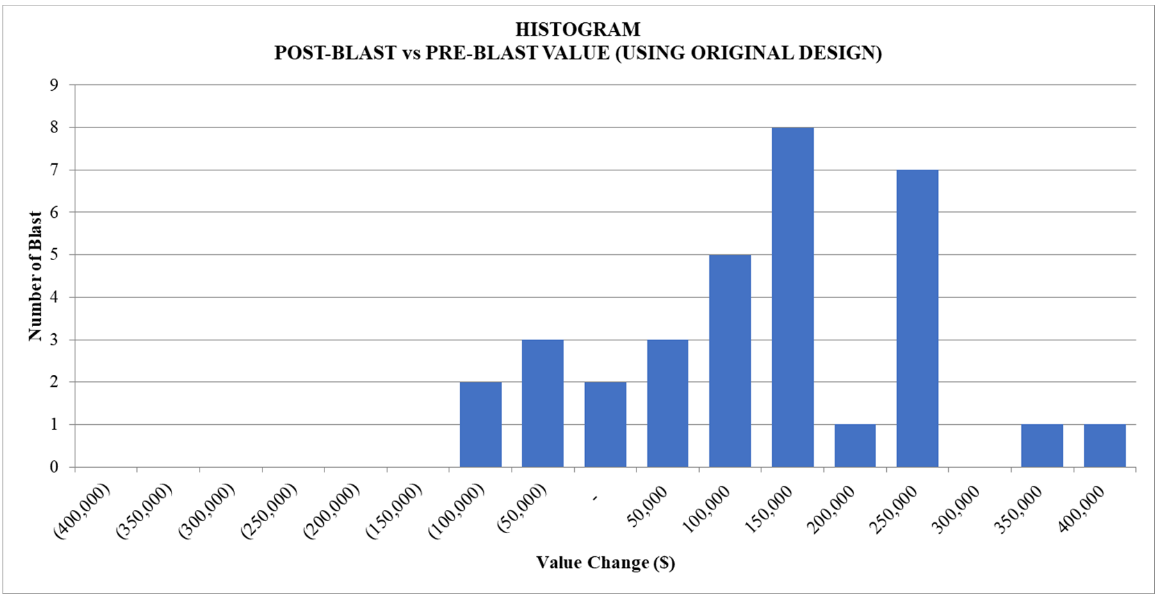


FIG 7 – Value change caused by the original blast design.

TABLE 1

Original blast design statistics (value).

Mean	104 664
Standard Error	21 839
Median	115 286
Standard Deviation	125 455
Minimum	(143 191)
Maximum	392 255
Sum	3 453 903
Count	33

The worst blast design

By comparing *in situ* grade control value possible with the value possible in the blast designs with the lowest outcomes (worst blast design), risk can be evaluated.

It is possible that these blast designs could have been used, had another blaster designed the blasts, or even if the same blaster had designed the blasts on a different day, with different goals. Twenty-four of the blasts reduced the value possible, and nine blasts increased the value possible. The average change was a reduction in value of $134 000, but there was a single blast that reduced the value possible by nearly $900 000. In total, the worst blast design could have resulted in a loss of over $4.4 M for these blasts (Figure 8 and Table 2).

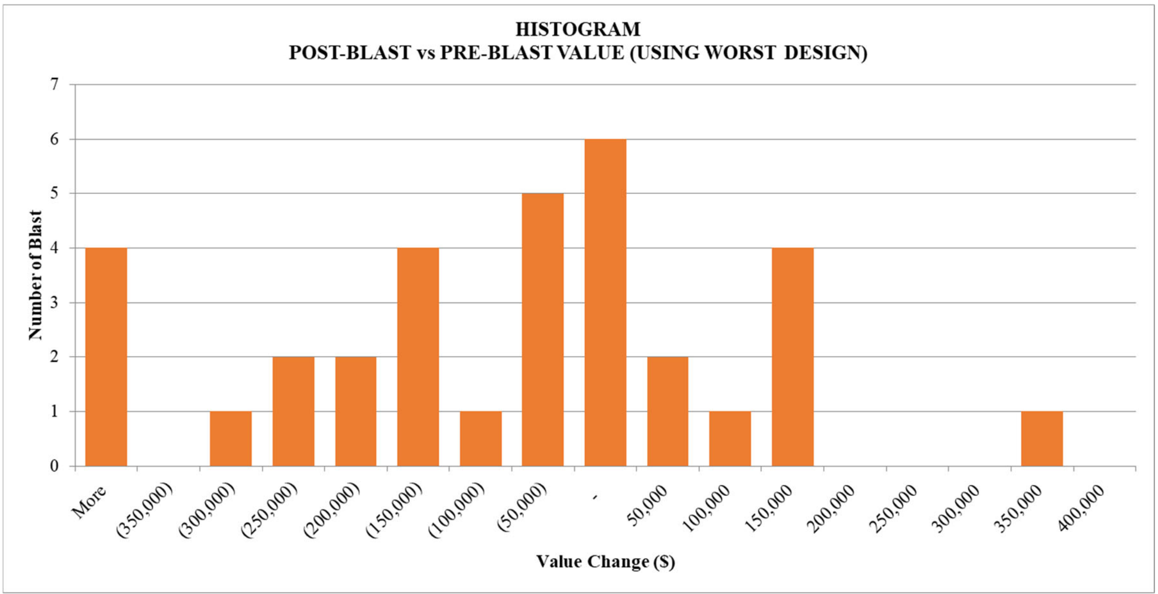


FIG 8 – Value change caused by the worst blast design.

TABLE 2

Worst blast design statistics ($).

Mean	(134 424)
Standard Error	45 877
Median	(71 249)
Standard Deviation	263 545
Minimum	(897 880)
Maximum	339 608
Sum	(4 435 986)
Count	33

The best blast design

By comparing *in situ* grade control value possible with the value possible in the blast designs with the highest outcomes (best blast design), opportunity can be evaluated.

It is possible that these blast designs could have been used, had another blaster designed the blasts, or the same blaster may have used these designs on a different day with different goals. Or, with the help of predictive modelling, these opportunities may have been uncovered and the blast designs used to create value. Nearly all these blasts created value (three designs reduced value possible), with the average increase of over $123 000. The total value increase possible with these blasts was over $4M (Figure 9 and Table 3).

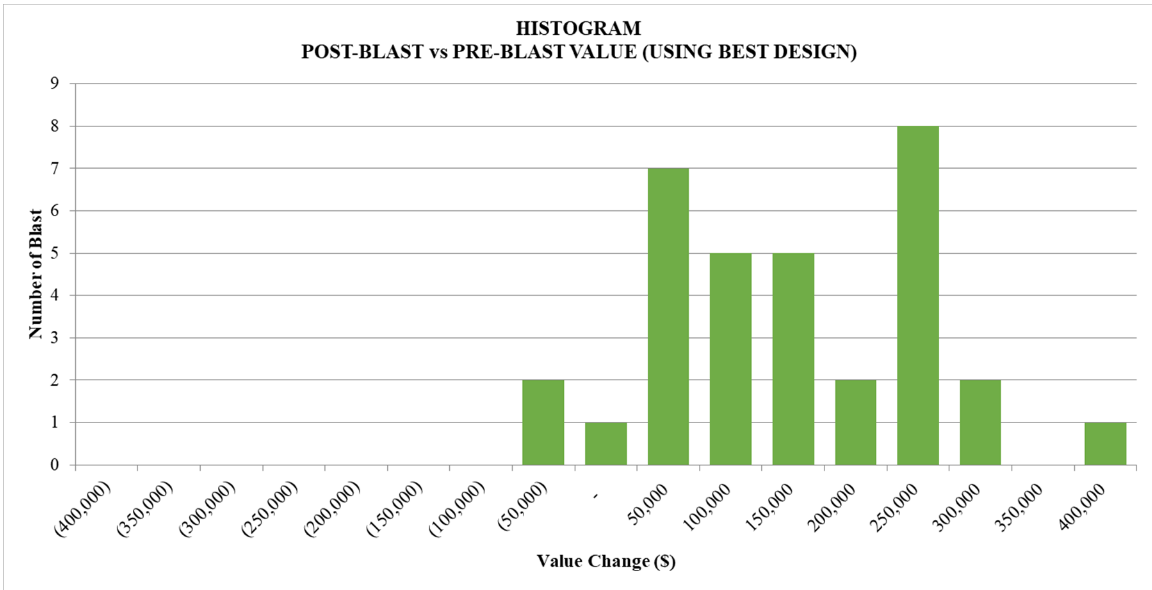


FIG 9 – Value change caused by the best blast design.

TABLE 3

Best blast design statistics.

Mean	123 339
Standard Error	19 202
Median	115 286
Standard Deviation	110 306
Minimum	(83 094)
Maximum	404 486
Sum	4 070 201
Count	33

Summary of comparisons

The hypothesis proved accurate in this case. The original blast design fell (on average) somewhere between the best possible design and the worst possible design. The best designs for value could have increased the value by $19 000 per blast (~18 per cent average value increase). The greatest value in prediction found in this study is the prevention of value loss. The range and magnitude in loss is tremendous. The average loss was $134 000, compared to an average gain of $123 000 for the best blast.

A process to quickly determine an optimal timing design for a blast does not presently exist, however some simple user interface changes could rectify those challenges. Re-timing blasts using blast design programs can be time-consuming, so the authors created a module inside of the Predictive Model that easily changed blast timing. Workshopping a new user experience would be required to determine if the module and proposed user experience changes would be easily adopted.

ANALYSIS

The results indicate that the hypothesis held true – that the original blasts designed fell somewhere between the highest possible value achievable and the lowest. In this case, the blasts were much closer to the highest value achievable than the lowest, but that will not always be true. The risk for these blasts is that they could have resulted in ~$4 M less profit that the plan would have shown, while the opportunity to increase the planned profit was nearly the same – $4 M over the planned target. For the 33 blasts analysed, the risk in reacting to blasts instead of predicting outcomes was definitely worth consideration.

Of significance in this analysis is the comparison between the original blast design and the optimal blast design. The original blast designs were rather close to the optimal designs. Whether that is by luck, because the blasters used rules of thumb, or because of a design procedure is not known. However, examination of the best blasts offers some clues. Table 4 lists the comparison results between *in situ* optimised polygons and polygons created post-blast when the best blast design was used.

TABLE 4

Best blast design results.

						Number of Blasts by Type			
Blast No	Insitu	Digging Direction	Pre-Blast Net ($)	Post-Blast Net ($)	(Post-blast) - (Pre-blast) ($)	Centerlift	Echelon	V	Original is Optimal?
1	Insitu-N	Original_Echelon-N	1,215,000	1,427,240	212,240		1		Y
2	Insitu-E	Echelon-E	3,653,470	3,831,191	177,721		1		
3	Insitu-N	Original_Centerlift-N	19,862,251	19,779,157	(83,094)	1			Y
4	Insitu-E	Original_Open V-E	9,312,462	9,423,416	110,954			1	Y
5	Insitu-W	Echelon-W	2,712,358	2,922,156	209,798		1		
6	Insitu-S	Open V-S	10,609,746	11,014,232	404,486			1	
7	Insitu-N	Original_Open V-N	6,257,272	6,457,554	200,282			1	Y
8	Insitu-S	Open V-S	5,707,940	5,690,054	(17,886)			1	
9	Insitu-E	Original_Echelon-E	3,446,505	3,570,381	123,876		1		Y
10	Insitu-E	Echelon-E	12,802,824	13,062,769	259,945		1		
11	Insitu-S	Original_Open V-S	10,025,716	10,171,321	145,605			1	Y
12	Insitu-S	Original_Echelon-S	995,385	1,238,409	243,024		1		Y
13	Insitu-S	Centerlift-S	6,899,609	7,120,202	220,593	1			
14	Insitu-E	Open V-E	2,696,481	2,904,206	207,725			1	
15	Insitu-W	Centerlift-W	8,274,791	8,478,051	203,260	1			
16	Insitu-N	Centerlift-N	5,408,209	5,417,736	9,526	1			
17	Insitu-E	Original_Open V-E	72,568	138,552	65,984			1	Y
18	Insitu-S	Original_Open V-S	3,588,811	3,680,257	91,446			1	Y
19	Insitu-S	Centerlift-S	1,784,038	1,731,330	(52,708)	1			
20	Insitu-W	Original_Open V-W	5,543,609	5,666,462	122,853			1	Y
21	Insitu-S	Centerlift-S	4,690,579	4,725,193	34,615	1			
22	Insitu-N	Original_Open V-N	16,369,226	16,563,539	194,314			1	Y
23	Insitu-E	Echelon-E	2,838,612	3,080,609	241,996		1		
24	Insitu-S	Centerlift-S	7,069,043	7,071,265	2,221	1			
25	Insitu-E	Open V-E	41,046	81,594	40,548			1	
26	Insitu-S	Original_Echelon-S	1,800,231	1,915,517	115,286		1		Y
27	Insitu-W	Original_Open V-W	777,002	850,749	73,747			1	Y
28	Insitu-E	Centerlift-E	3,667,634	3,754,874	87,240	1			
29	Insitu-S	Echelon-S	757,010	1,054,691	297,682		1		
30	Insitu-E	Original_Open V-E	11,709,721	11,755,104	45,383			1	Y
31	Insitu-E	Centerlift-E	5,939,992	6,003,334	63,342	1			
32	Insitu-N	Original_Open V-N	-	17,176	17,176			1	Y
33	Insitu-E	Echelon-E	238,535	239,557	1,022		1		
	Total		**176,767,678**	**180,837,879**	**4,070,201**	**9**	**10**	**14**	**15**

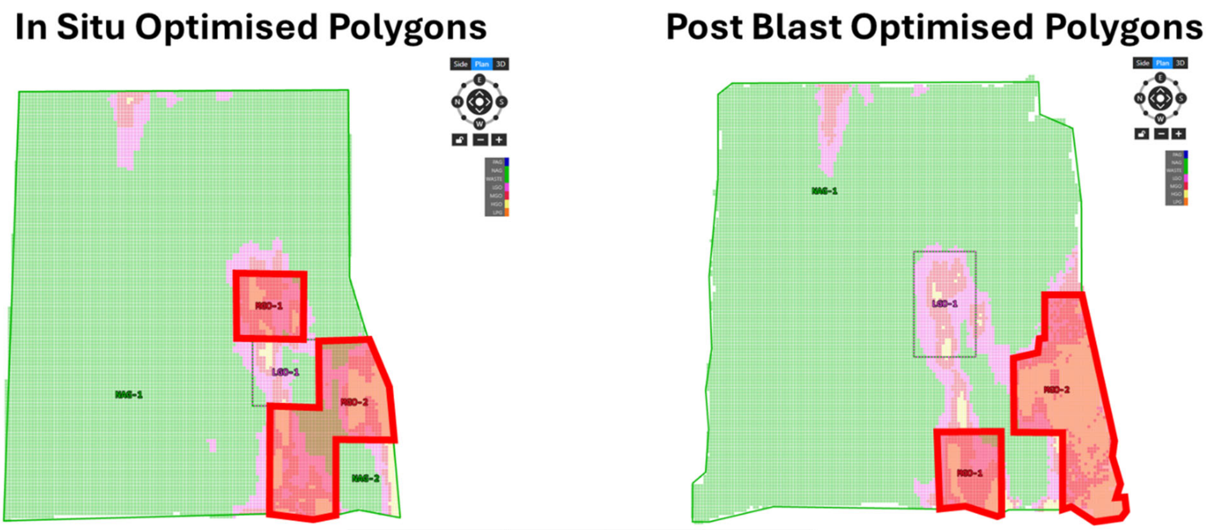
In nearly half of the blasts, the original blast design was the best. None of the original blast designs which were determined to have the optimised outcome used a centrelift design, which is typically discouraged for grade control blasts is it is the most variable. However in nine blasts, centrelift initiation designs resulted in the best outcomes.

Before predictive modelling, blasters used ‘rules of thumb’ or SOPs to dictate blast designs chosen. The objective was to minimise the erratic heave and the uncertainty that existed in the chaotic regions of convergence, of which the centrelift has the maximum amount of chaos in the initiation region. Julian, La Rosa and Craft (2023) describes examples of rules of thumb have guided blasters for decades, but in some cases, are no longer particularly relevant. Given uncertainty in the centrelift, it is still possible that best practice to use other designs in blasts where ore and waste are both present. More data is needed to determine if these best practice recommendations should be changed.

Mechanisms causing value increases or decreases

Blasting changes the shape of the rock through swell and deformation. Ore Loss and Dilution are caused by the application of 2D digging constraints (grade control polygons) to the 3D volume. Since grade control polygons cannot bend perfectly around ore/waste contacts, some inevitable inefficiencies exist – often referred to as ore loss and dilution. These terms are frequently used as proxies for economic value. The digline optimiser inside of the Predictive Model attempts to create delineations that result in the highest value possible (given constraints on polygon shape, size, and CPU processing capacity), which consider mining direction, face angle, and classification rules. Since the *in situ* model and the post-blast model are different shapes, the resulting value contained in optimised polygons will, naturally, be different (Hunt, 2022).

To illustrate the effects of value change caused by the blast, consider Figure 10. Shown is a plan view of the *in situ* composite model and the post-blast composite model. The amount of ore loss present increases post-blast by over 10 000 t, dilution goes down by over 20 000 t, and the value increases by $65 000 (nearly doubles from *in situ*). If a mine's stated goal was to 'reduce ore loss', they would have lost money.



Polygons	Ore Loss (t)	Dilution (t)	Net Profit ($)
In Situ	14,505	31,581	72,568
Post Blast	24,777	11,351	138,552
Diff caused by blast	10,272	(20,230)	65,984

FIG 10 – Blast 17 *In situ* and Post-blast Polygons Compared (Red is Ore).

The mechanisms for changing value are not always clear, but more often than not, the MMU (minimum mining unit) is revealed to be the reason for the disconnect. The difference between *in situ* and post-blast optimised polygons in this blast (Figure 10) is very evident, particularly in the red ore polygon on the right edge of the blast. In the *in situ* optimised polygons, the strip of waste down the centre of that ore polygon is too narrow to mine without accidentally sending ore into the trucks hauling waste. But, after the blast spreads the ore out just a bit more, this area becomes two separate polygons. In contrast, the small ore polygon towards the top becomes diluted until the area cannot be profitably mined as ore, and instead is designated as mineralised waste. The mineralisation at this mine is quite narrow in some places. When the rock is blasted, it spreads out. If it spreads into an advantageous direction, what was unprofitable *in situ* due to the massive dilution required to excavate it can suddenly become profitable.

MMU is an important constraint because it describes the minimum polygon size that a grade control geologist believes is practical to mine without contamination from other blocks using the excavation equipment planned. Certainly, different equipment will have different MMU capacities. Backhoes may be able to dig 5 × 5 m shapes, but they cannot handle tall muck piles in a single flitch, while front shovels may need far greater MMU sizes but can handle 15 m high working faces). In the authors' experiences, different people at the same mine may have different opinions on minimal mineable shapes. For example, one geologist at a mine may say 10 × 10 m while another says 'No, 10 × 15 m is the smallest shape we can mine'. In this study, 20 × 20 m was used as the MMU, and that appears to be the driving force behind the value changes.

CONCLUSION

The processing of blasting subjects ore to complex movement dynamics. When the value of optimised mining polygons generated on the *in situ* grade control model are compared to optimised mining polygons generated on the post-blast model, a difference will always exist. A negative change represents a loss of value and metal for the operation, while a positive value represents an increased yield and metal. Optimisation of mining polygons on the post-blast muck pile is to little effect if the value has been degraded by a poor blast design.

The impact of the blast design on post-blast value was investigated by simulating various blast designs on 33 blasts at a Canadian gold mine. Optimised blasts were estimated to generated an additional $18 600 over the original designs. Critically, the simulations identified blast outcomes with substantially poorer outcomes. The worst blast designs degraded value by an average of $239 000 compared to the original designs. The potential loss of value and metal is avoidable and warrants the procedural evaluation of blast outcomes to mitigate this risk.

This study indicated significant opportunities for predictive blast modelling. However, systems for incorporating that knowledge into mine planning and reconciliation are lacking. Further work should be performed with a mine that is open to predictive planning to determine steps required, change management processes, and the results measured against the opportunity predicted.

REFERENCES

Hall, B and Hunt, W, 2019. Implementing 3D Ore Control at Red Dog Mine, presented at CIM 2019 Convention. Available from <https://www.ocblasting.com/s/2019-CIM_Hall-and-Hunt.pdf> [Accessed: 22 February 2021].

Hunt, W and La Rosa, D, 2023. Advantages in Using Real-Time Blasting Simulation in Surface Blast Planning and Grade Control, San Antonio, International Society of Explosives Engineers (ISEE).

Hunt, W and La Rosa, D, 2019a. How to Use Heave, Movement and Ore Block Optimization to Increase Grade and Decrease Dilution, Denver, SME.

Hunt, W and La Rosa, D, 2019b. To Flitch or Not To Flitch, Denver, Society for Mining, Metallurgy and Exploration (SME).

Hunt, W, Julian, L, La Rosa, D and Ruiseco, J R, 2022. Economic Ore Control (EOC), Salt Lake City, Society for Mining, Metallurgy and Exploration (SME), presentation.

Isaaks, E, 2019. Don't be Misled by Ore Loss and Dilution Calculations, Denver, Isaaks and Co.

Julian, L, La Rosa, D and Craft, M, 2023. A Review of Contemporary Blast Design Data and Rules of Thumb, San Antonio, International Society of Explosives Engineers (ISEE).

Poupeau, B, Hunt, W and La Rosa, D, 2019. Blast induced movement: the missing step in achieving realistic reconciliations, in *Proceedings of Mining Geology 2019*, pp 309–327 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Preece, D S and Taylor, L M, 1990. Spherical element bulking mechanisms for modelling blast induce rock motion, in *Proceedings of the 3rd Int Symp on Rock Fragmentation by Blasting*, pp 189–194 (Society of Experimental Mechanics).

Preece, D S, Chung, S H and Tidman, J P, 1998. An assessment of ore waste and dilution resulting from buffer/choke blasting in surface gold mines, in *Proceedings of the 14th Annual Symp on Explosives and Basting Research*, pp 137–146 (Society of Experimental Mechanics).

Taylor, S, 1995. Blast induced movement and its effect on grade dilution at the Coeur Rochester Mine, Reno, thesis, University of Nevada Reno.

Yang, R R and Kavetsky, A, 1990. A three dimensional model of muckpile formation and grade boundary movement in open pit blasting, *International Journal of Mining and Geological Engineering*, pp 18–34.

Hyperspectral image processing and analysis for exploration in the mining industry

D Kumar[1], S Prakash[2] and M Danish[3]

1. Dy Director, IIT(ISM) Dhanbad and Project Director, TEXMiN Foundation, Dhanbad, Jharkhand 826004, India. Email: dheeraj@iitism.ac.in
2. CEO, TEXMiN Foundation: Dhanbad, Jharkhand 826004, India. Email: ceo@texmin.in
3. CBDO, TEXMiN Foundation: Dhanbad, Jharkhand 826004, India. Email: cbdo@texmin.in

ABSTRACT

The green energy transition is speculated to cause an increase in the demand for raw materials while recycling rates are improving; discoveries are required to maintain supply. Geological remote sensing offers a cost-effective way of exploring mineral resources. While satellite and airborne imaging are routinely used for exploration targeting, a gap remains at the outcrop scale. Hyperspectral imaging (HSI) is advantageous for large-scale regional mapping, typically performed from satellite or airborne platforms. Accurately mapping geological lithologies remains challenging in inaccessible areas, such as rough terrain or mine sites. Proximal sensing techniques can boost geological activities' reliability, safety, and efficiency in exploration or during mining activities. It also generates objective, reproducible results and valuable raw data that can be archived, further processed, and re-interpreted. Ground-based hyperspectral imaging of outcrops has steadily increased during the last decade due to sensor development and better processing routines.

There is often a big technology gap related to mineral mapping, integration of images and spectra (reduction in manual identification of minerals and types) and hyperspectral data visualisation through remote sensing.

TEXMiN Foundation, in collaboration with its industry partner Dassault Systemes Foundation, carried out the project, 'Developing Hyperspectral Image Processing and Analysis, build a rich library of Hyperspectral images of a vast range of minerals from India which will help in increasing prediction accuracy of mineral deposit for mining exploration'.

The project covered a detailed scope underpinning:

- Develop a Spectral Library of several mineral deposits in India, which consists of a hyperspectral signature of various minerals and is mapped with its physical properties. Such a database/ library will be useful for mapping and extracting the features embedded in input images.
- It also aimed to build a framework that supports hyperspectral imaging for standard computer vision methods for processing, augmenting, and training models for hyperspectral images.
- Such a rich library of hyperspectral images of minerals will help increase the accuracy of the prediction of mineral deposits.
- The library will aim to help ease the computations for future research.

The current paper delineates the findings and outcomes in detail, focusing on developing a spectral library that will have a database consisting of various hyperspectral images of mineral deposits of India that will be used to map and extract the features embedded in input images.

QGIS software with AVHYAS (Advanced Hyperspectral Data Analysis) Python-3-based plug-in, an open-based software designed to process and analyse hyperspectral (Hx) images, has been used as a tool to process the present and future Hx airborne/spaceborne sensor data and provide access to advanced algorithms for Hx data processing.

INTRODUCTION

We have stumbled over QGIS software with AVHYAS (Advanced Hyperspectral Data Analysis) Python-3-based plug-in, an open-based software designed to process and analyse hyperspectral

(Hx) images. It is developed to guarantee total usage of present and future Hx airborne or spaceborne sensors and provides access to advanced algorithms for Hx data processing.

Hyperspectral image analysis and processes comprises of the following steps:

- data acquisition from spectral libraries or spectral-radiometer
- data storage on cloud servers
- sensor and reflectance calibration
- atmospheric correction and data preprocessing
- data annotation through spectral matching
- endmember selection
- image classification.

Data Acquisition – There are multiple sources from which hyperspectral data can be acquired, such as Earth Explorer, USGS, and other spectral libraries. The most often used data source is the Earth Explorer, where we can enclose the area of interest with the help of coordinates on the map (can also be done with the help of predefined areas and/or circles or user-defined radius and centre) and subsequently specify the searching criteria, such as date range, cloud coverage, months which will yield the satellites, the data of which we need for our purpose.

One can select multiple satellites at once, although, for hyperspectral image analysis and processing, we would require EO-1 Hyperion data, where EO-1 is the satellite's name, and Hyperion denotes hyperspectral images. As a result, various patches of land will be shown that can be downloaded in .L1R,.L1Gst,.L1T and .GeoTiff formats.

For our purpose, we need to download the image in.L1R format, which comprises the radiance file of the HSI along with the metadata (.MET) and auxiliary files (.AUX). Such data can be used for analysis and practice purposes, and for the development scope of our work, we are yet to receive the AVIRIS-NG satellite hyperspectral data. Data can be stored on cloud storage servers as the size of each image file can range between 200–300 MBs.

Atmospheric Correction – Because the solar radiation on the sun-surface-sensor path in the 0.4–2.5 μm visible and near-IR spectral regions is subject to absorption and scattering by atmospheric gases and aerosols, the hyperspectral imaging data contains atmospheric effects.

To use hyperspectral imaging data for quantitative remote sensing of land surfaces and ocean colour, the atmospheric effects must be removed. Various methods such as ATREM, QUAC, FLAASH, 5S/6S MODTRAN-4 database code and most recently, radiative transfer modelling methods have been developed. Different materials, from rocks to minerals, can have varying spectra after the spectral reflectance has been cleaned for atmospheric errors.

Multispectral image analysis methods largely depend on the spatial aspects of the objects of interest, such as their shape, texture, and spectral properties in the few wavelength bands in which the images are acquired. It is difficult with such data to discriminate between vegetation categories, eutrophication of lakes, identification of the presence or absence of specific elements or compounds in soil or rock, and so on. For this purpose, a highly detailed spectral characterisation of the target is required, and the field of hyperspectral remote sensing has evolved to address this need. Hyperspectral remote sensing or imaging spectroscopy involves acquiring images in many narrow contiguous spectral bands (typically>100).

Consequently, hyperspectral images are better described as image cubes with two spatial and spectral dimensions. For high throughput processing, wavelength-specific criteria for high-speed quality control and analysis can be readily deployed in an in-line manner along the production process line, starting with raw material blending to in-process characterisation and raw mill/clinker optimisation. This capability yields mineral processors the benefits of reducing the time, temperature, and duration of kiln processing while providing greater quality control over the composition of the final product. Depending on the spectral characteristics of different rocks, researchers can extract information about various rock types and apply hyperspectral remote sensing from qualitative analysis to quantitative recognition.

METHODOLOGY

The three broad categories of operations conducted on hyperspectral images are data acquisition, data representation, image processing, and classification. For data acquisition, both spectral and spatial information must be recorded with the help of hyperspectral and multispectral cameras.

After the data has been acquired and stored, it needs to be represented in a suitable format which can be parsed for processing and classification. The hyperspectral imaging produces a 3D structure of the image referred to as the data cube. Using this data cube, pixel and spatial information are extracted using spectral values defined as a function of wavelength.

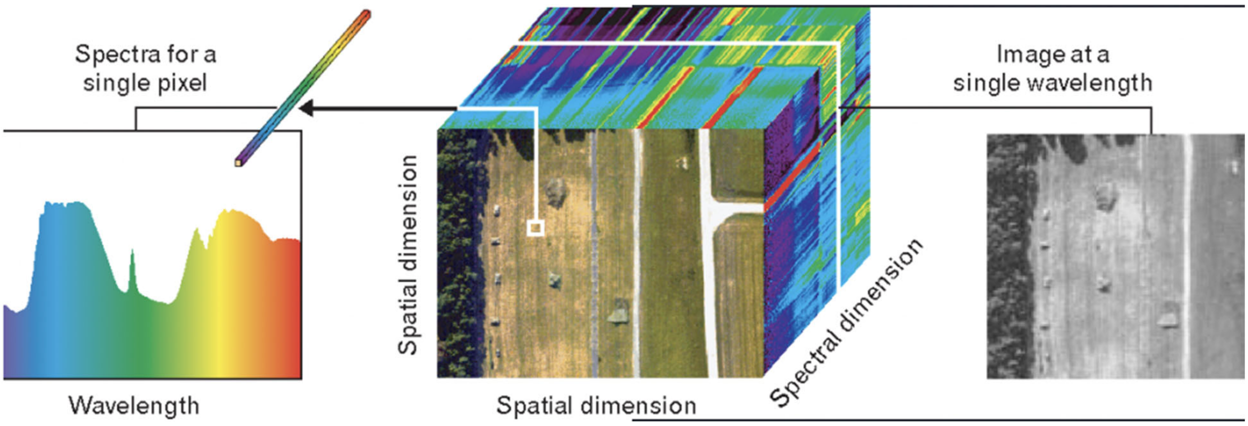


FIG 1 – Data representation.

Image processing involves the following steps:

- Increasing the spatial resolution.
- Performing radiometric correction, involving:
  - striping
  - missing lines
  - illumination and view-angle effects
  - sensor calibration
  - terrain effects.
- Performing atmospheric correction using different packages and MODTRAN-based code.
- Topographic correction.

In image classification, the hyperspectral image is classified as 'X' mineral present and information on its physical and chemical properties are also extracted. It primarily involves two steps:

- **Spectral Unmixing** – Endmember extraction of the hyperspectral data using pure pixels is done.
- **Spectral Matching and Classification** – Interpret the pixel spectra by performing spectral matching. Spectral matching identifies the class of an endmember material by comparing its spectra with one or more reference spectra. The reference data consists of pure spectral signatures of materials, which are available as spectral libraries. Some methods for spectral matching are as follows:
  - spectral angle mapper
  - spectral information divergence
  - combination of SID and SAM

- normalised spectra similarity score
- we can also classify the spectral images using machine learning techniques.

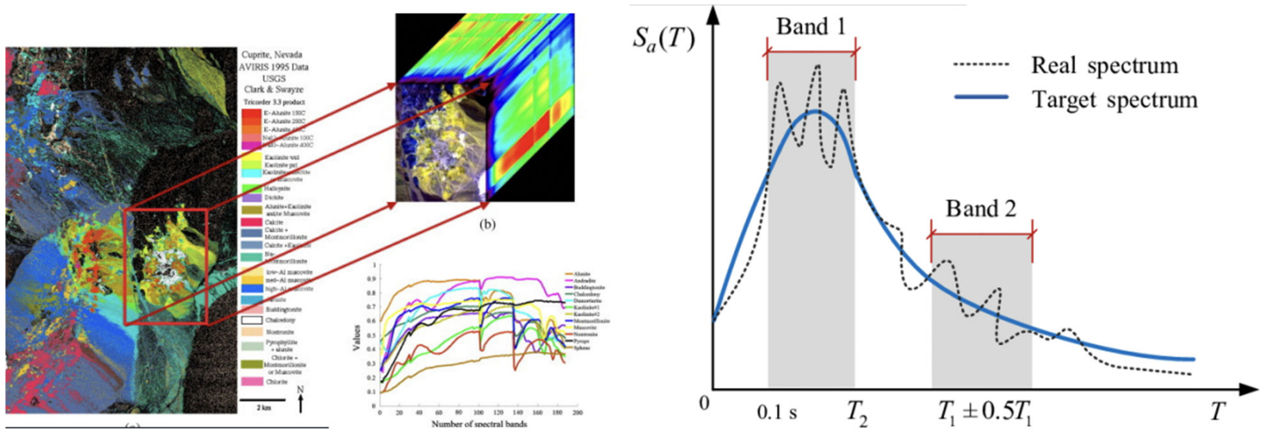


FIG 2 – Spectral matching and classification.

The process flow is summarised in Figure 3.

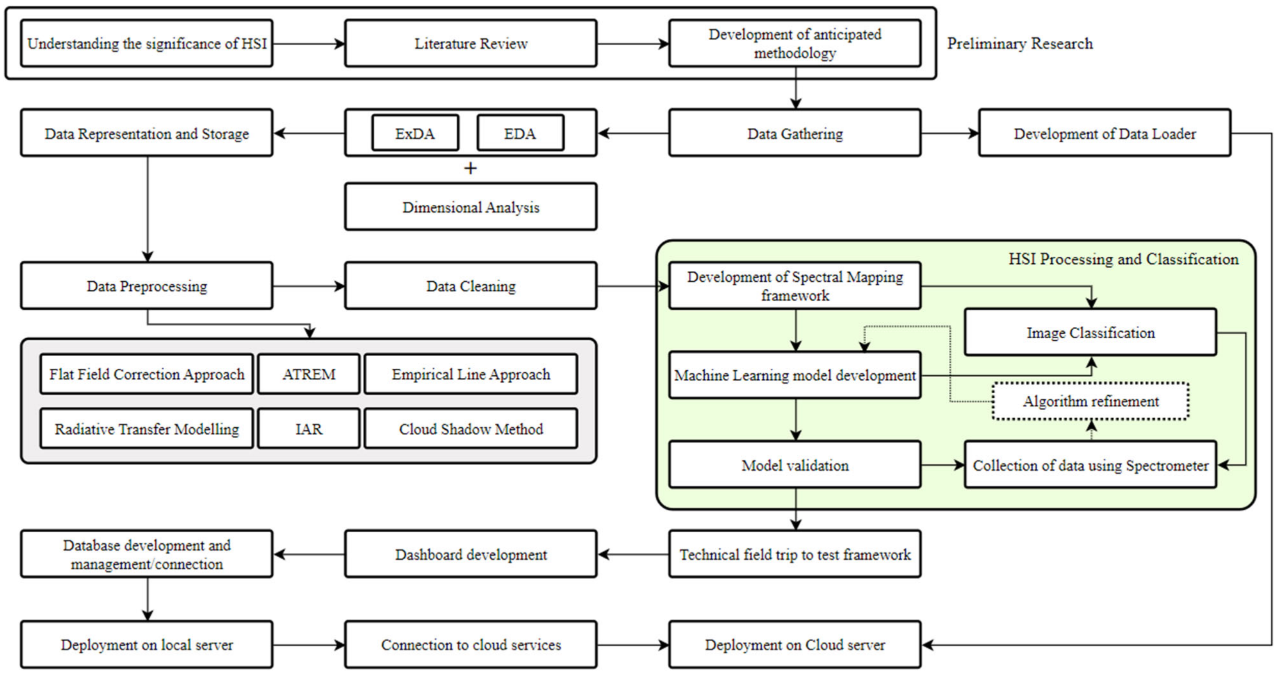


FIG 3 – Process flow sheet for hyperspectral image processing and analysis for exploration in the mining industry.

MILESTONES ACHIEVED AND CURRENT UNDERSTANDING

Minerals and rocks generally have diagnostic spectral absorption bands in the spectral range of 400–2500 nm. Hyperspectral remote sensing can effectively capture spectral characteristics. Mineral composition information can be inverted and identified according to the spectrum. As a result, rock and mineral classification, mapping, and resource exploration can be performed. Some spectral libraries and expert system software have been established to map minerals using hyperspectral images.

For example, each pixel spectrum in the AVIRIS image was compared to the ranges of more than 300 substances in the USGS spectral library for discrimination and classification. Depending on the spectral characteristics of different rocks, researchers can extract information about various rock types and apply hyperspectral remote sensing from qualitative analysis to quantitative recognition.

We extract rock information by image processing according to different rocks' spectral characteristics and apply hyperspectral remote sensing to geoscience from qualitative research to quantitative identification. In general, there are two groups of effective methods. The first includes minimum noise separation (MNF) and PC transformation to reduce the dimensions of hyperspectral images and compress the information into an image with a specified dimension (n). We use n-D and PPI tools to analyse the MNF result image and find pure pixels in the spectrum. These pure pixels become the sample endmembers, known as the endmember selection process, extract the endmembers spectral curves, and establish a spectral library for classification. The resulting MNF images have been shown to play an important role in rock recognition and boundary delineation, especially for the main local minerals. The second group includes mineral pixel analysis and classification based on spectral libraries such as spectral angle mapping (SAM), spectral feature fitting, spectral separation (UNMIX), and mixture-tuned matched filtering (MTMF). SAM and MTMF were the most practical of these methods in the study.

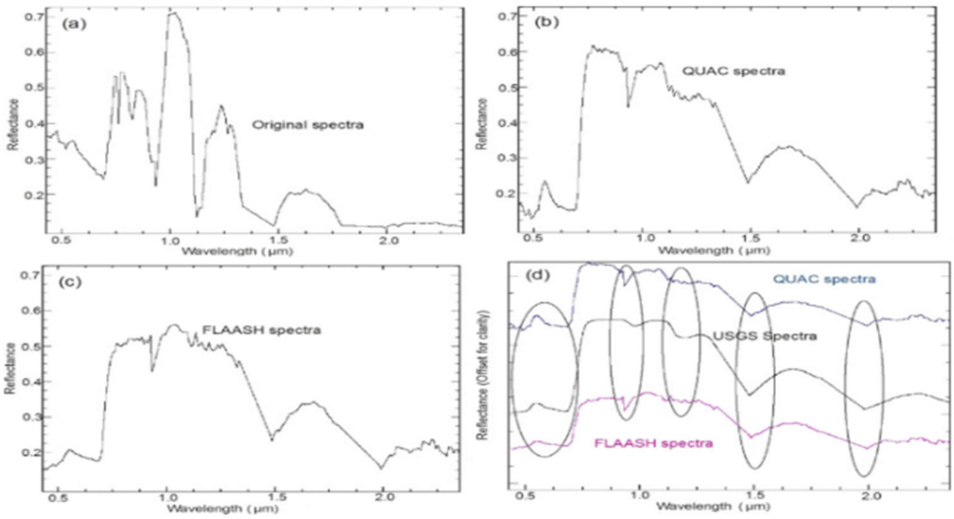


FIG 4 – Atmospheric correction explained through reflectance curves.

ACKNOWLEDGEMENT

The CSR funding support from La Foundation, Dassault Systemes, and TEXMiN Foundation IIT (ISM) Dhanbad has been duly acknowledged.

Unlocking mine productivity by changing-the-equation on the where, what and when of orebody characterisation

P Leckie[1], S Warden[2] and T Neville[3]

1. Senior Manager, Orebody Intelligence, Orica Digital Solutions, Perth WA 6106.
   Email: peter.leckie@orica.com
2. Senior Geophysicist, Orica Digital Solutions, East Melbourne Vic 3002.
   Email: sheldon.warden@orica.com
3. Principal Research Fellow, Orebody Intelligence, Orica Digital Solutions, Perth WA 6106.
   Email: tom.neville@orica.com

ABSTRACT

At its simplest, the classification and characterisation of an orebody is a matter of *Where*, *What* and *When*. *Where* and with what spatial resolution are measurements taken, *What* properties are measured, and *When* are the data acquired, processed, and delivered to create the most value.

This paper delves into how existing and near-term advances in measurement technologies, field automation, and whole-system-digitisation are combining to open new routes for mine and exploration productivity improvement.

Commencing when the initial exploration hole is dug, the advancement in deployment of survey technology—from expert-operated, to driller-operated, to driller-integrated—is used to demonstrate a template for adoption of higher technology measurements. We then introduce and discuss the multi-use measurement as offering outsized returns from a single measurement run, highlighting two new technologies that acquire rock strength while drilling and downhole assay data as examples.

For rock strength, we highlight a novel approach to determining Uniaxial Compressive Strength (UCS) while drilling, its relationship to and advantages over Mechanical Specific Energy (MSE), and how it offers utility to multiple downstream processes. For downhole assay, we detail how a back-to-physics approach to Pulsed Fast and Thermal Neutron Activation (PFTNA) analysis offers significant advantages over other measurement methods and earlier implementations of PFTNA, generating a rich data set that can significantly extend and improve the information on which mining decisions are made.

Finally, we discuss the possibilities enabled via optimising data delivery, collection, and curation—noting a fundamental limitation of historical systems and exploring the possibilities that will be unlocked by soon-to-market solutions that better enable Orebody Characterisation data to (virtually) move in space and time with rock material post-blasting.

Ultimately, the value of optimising the *Where*, *What*, and *When* from point of measurement to the moment it generates maximum value will create greater life-of-asset production for a lower cost and energy input.

INTRODUCTION

Optimising the *Where*, *What* and *When* across the data set collected from early exploration to the moments before blasting has application in improving mine productivity well beyond incorporation into the various models used in mine planning.

This paper discusses concepts and technologies to maximise the utility of this data set by:

- Integrating measurement hardware and software further into drilling workflows (*The Where*).
- Offering direct measurements and multiple-use data sets that advance the state-of-the-art (*The What*).
- Improving custody and utility of the data set as it moves in space and time post blasting (*The When*).

The concept of *drilling-integrated-measurement workflows* is introduced. The benefit of such workflows in enabling denser and higher quality measurements using existing field personnel is demonstrated via a case study featuring drill core orientation technology. Incorporation of this design ethos for deployment of future measurements in this fashion will see them utilised to their greatest potential.

Next, two new measurement solutions are introduced that deliver *multi-use-measurements* (UCS-while-drilling and downhole assay) that offer outsized value for mine productivity improvements.

Finally, we explore how the true value of these measurements will be delivered via productivity improvement initiatives, enabled by looking beyond the block model as the final home for Orebody Characterisation information.

THE WHERE – THE FUTURE STARTS WITH THE FIRST BOREHOLE

Whilst there are many exploration steps before commencing a drilling campaign (eg surface exploration, rock, and soil sampling), it is the drilling of the first exploration boreholes and associated surveying and core sampling that forms the foundation on which the planning and design of a mine is built. Because all subsequent data collection is associated with the spatial and directional measurements of these early sub-surface investigations, there is an outsized premium on ensuring that these measurements are plentiful and accurate.

As such, this paper highlights the advancement of survey deployment approaches and their impact on measurement quality as a design ethos that should be applied as widely as possible to aid both the uptake and acceptance of new technologies.

Over the last 15 years, survey workflows have moved from being expert-operated, to driller-operated, to drilling-integrated, of which the key features to highlight are:

- **Expert-Operated** uses complex equipment which requires a specific skill set to deploy. This means that the measurement can only be undertaken when the expert is available and has been granted access to the mine site. Running the survey alongside the drilling operations implies risks inherent to coactivity. If the measurements cannot be conducted during maintenance or other necessary downtime, the survey negatively impacts the driller's productivity.
- **Driller-Operated** uses robust hardware and gives the responsibility of measurement to the driller, which may come at a price of reduced quality but with the benefit of added productivity and lower personnel costs.
- **Drilling-Integrated** uses the combination of hardware and software to instrument the drilling workflow, enabling measurements to be taken without interruption to the drilling operation. Remotely connected solutions can help maintain measurement quality, with off-site experts able to QC incoming data and metadata and guide the driller accordingly. Surveying on the overshot is an early example of a drilling-integrated measurement workflow, and a demonstration that *while-drilling* arrangements are not the only way to deliver drilling-integrated workflows.

Whilst these concepts are not new, it is the authors' view that insufficient consideration of these principles are a material driver behind poor adoption of technologies that could otherwise offer significant value when considered from a measurement perspective alone. This view is supported by the well-established Technology Acceptance Model (TAM) (Davis, 1989); this purports that the two dominant factors influencing the uptake of technology are the technology's perceived ease of use and the technology's perceived usefulness.

A demonstration of the benefits of a drilling-integrated-measurement workflow is offered by the widely used Axis Champ Ori™ core orientation tool. The tool replaces a spindle bushing on the back-end assembly of the inner tube, thus turning a simple piece of metal into a measurement device without asking the driller to lengthen or modify their equipment, nor alter their workflow.

An underground gold miner in Australia started testing this solution in late 2021 to improve their success rate of core orientation measurements with the results subsequently collated and published

(Hunter, 2024). Over 22 605 data points, the drilling-integrated technology achieved a successful survey rate of 87.9 per cent against the long-term prior average of 74.9 per cent, a 50 per cent reduction in failed surveys (Table 1).

TABLE 1

Results of long-term Champ Ori™ reliability investigation.

Period in which Champ Ori™ exclusively used	Oct 2021 to Mar 2023
Total data points collected in competent ground over the period	22 605
Data collected in competent ground and reliable Ori and makes geological sense	19 354
Success rate	87.9% (12.1% fail rate)
Success Rate before Champ Ori™ Application (pre-June 2021)	75.9% (24.1% fail rate)
Improvement	12% (fail rate down 50%)

These results demonstrate that a drilling-integrated-measurement-workflow approach supports not only technology uptake, but the plentiful and accurate collection of Orebody Characterisation data.

THE WHAT – A MULTI-USE MEASUREMENT SUITE

After considering where the measurements are taken, the next opportunity lies with the *What*: What are we measuring, and what measurement (or measurement suite) will deliver the maximum utility with the minimum disruption to workflows. This introduces the concept of the *multi-use measurement*; defined as either:

- single measurements that are critical inputs to multiple optimisation decisions, or
- a single measurement process that generates multiple streams of data.

This discussion will highlight new developments in measuring rock strength (Uniaxial Compressive Strength, or UCS, collected while drilling) and collecting assay data downhole using Pulsed Fast and Thermal Neutron Activation (PFTNA) techniques, which the authors are defining as multi-use-measurements because:

- UCS is a single property that enables decisions at multiple downstream stages, ie it can enable optimisation of blast pattern spacing and loading, blend management, and mill control.
- In-field elemental analysis generated by PFTNA of downhole rock formations (hereby referred to as downhole assay), generates a suite of measurement data on a single run that enables a step-change in the information set used for decision-making in blast design, dilution control, load and haul, and processing.

Rock strength measurement while drilling

Whilst there have been and continue to be ongoing efforts (Segui and Higgins, 2002; Isheyskiy and Sanchidrián, 2020) to use operational drill-rig parameters (eg Mechanical Specific Energy, or MSE) derived from drilling parameters (eg weight on bit, torque on bit, rate of penetration) to infer properties of the rock being drilled, reliable application of this parameter is often curtailed by shortcomings:

- MWD sensor maintenance relies on the driller, who (as per the aforementioned Technology Acceptance Model) may not perceive usefulness in the measurement and neglect maintenance.
- MSE is the energy input by the drill rig *at the ground surface* to break a unit volume of rock. While it contains information about the strength of the rocks being drilled, it is also sensitive to

drilling efficiency, influenced by the condition of the bit (eg bit wear) and the technique of the driller.

The outcome is that MSE is not a reliable measure of the actual rock strength, limiting its use at time of measurement, let alone as a multi-use-measurement applied downstream.

An alternative approach is to seek Uniaxial Compressive Strength (also known as Unconfined Compressive Strength, or UCS) instead of MSE. UCS is a measure of the rock specific energy, ie the energy needed to break a unit volume of rock. It is the strength recorded at the point of failure of an axial column of rock (ie a length of diamond drill core), and is considered multi-use because it is an objective property of the rock that has been demonstrated to be a key parameter for optimisation of:

- Post-blast fragmentation (Nainggolan *et al*, 2018), which is not only a key output measure of blast efficiency but a key determinant of truck and shovel performance (Dotto and Pourrahimian, 2018).
- Truck and shovel performance (Adesida, 2021).
- Crusher performance (Olaleye, 2010).

A way to deliver this is by using a novel axial delay measurement derived from the acceleration induced in the drill string by the interaction of the bit with the rock during drilling (Griffiths, Warden and Alonso, 2023), known commercially as RHINO™. The delays measured using RHINO™ are strongly correlated to UCS and are independent of drilling practices and drill bit conditions (Figure 1).

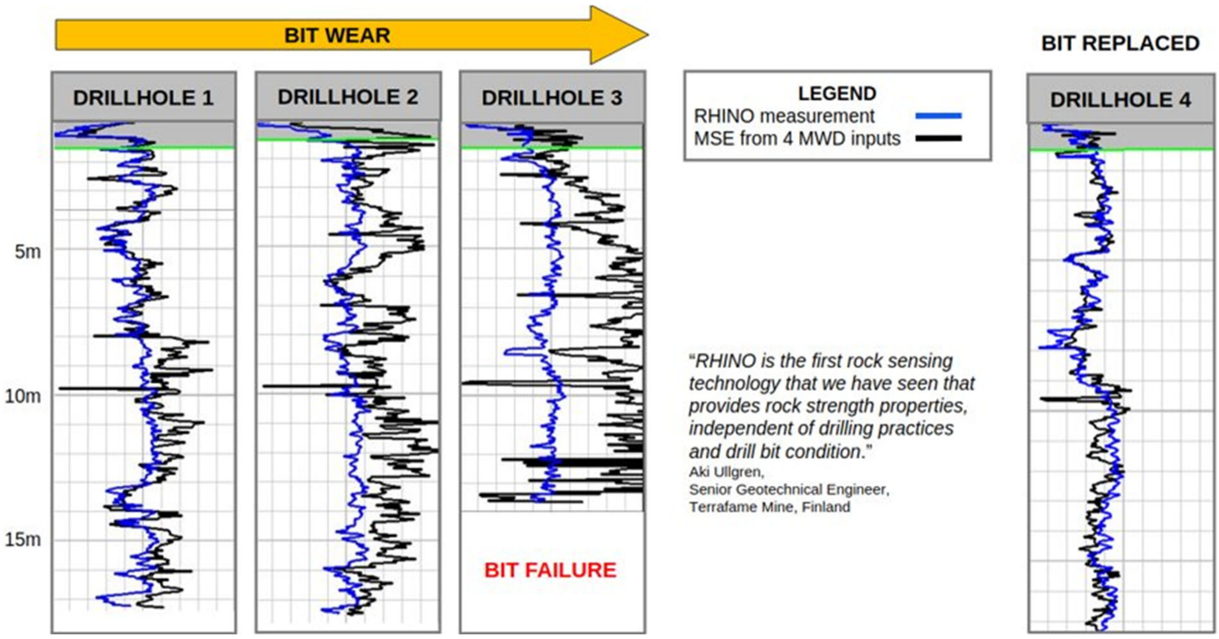


FIG 1 – Calibrated RHINO™ logs (in blue) and Mechanical Specific Energy (MSE) logs (in black) acquired while drilling four consecutive drill holes at the Terrafame polymetallic mine in Kainuu, Finland. As the first three holes were drilled, drill bit wear kept increasing until bit failure. Drill hole four was drilled immediately after the bit was replaced. While initially in good agreement with RHINO™ data, the MSE logs become erratic as bit wear progresses; upon replacement of the bit, both logs display the same relative variations again. This highlights the fact that RHINO™ is not sensitive to drill bit condition.

RHINO™'s delivery of UCS-while-drilling changes the equation on Orebody Characterisation by directly delivering a *Drilling-Integrated-Multi-Use* measurement that has well documented links to performance of key mine site operations. Application of the measurement for delivery of these improvements is covered at a later stage of this discussion.

Downhole assay

One exciting trend of recent years is the move of chemical analysis from the laboratory to the field, using a variety of spectroscopic techniques such as X-ray fluorescence (XRF), laser-induced breakdown spectroscopy (LIBS), and neutron activation analysis (NAA). These are being employed to generate elemental analysis of rock samples throughout the mining value chain (Exploration, Grade Control, Drill and Blast, Mill Feed) using different deployment techniques.

XRF has seen widespread deployment, from the near ubiquitous handheld analysers to automated systems for scanning core, in-bucket analysis systems, and online conveyor belt analysers. LIBS is seeing a similar range of deployment methods. Both technologies can provide rapid and comprehensive chemical analysis, however a key shortcoming of both techniques is the limited depth of penetration and volume of investigation of an individual measurement. Therefore, a typical application of these technologies requires multiple measurements to be made of the surface of a sample to characterise the bulk chemistry of the sample. Due to the significantly higher penetration of neutrons into a sample than the low energy photons used in XRF and LIBS, neutron activation analysis allows a true bulk characterisation measurement of a sample volume that may be as much as a million times larger than that sensed by an XRF or LIBS measurement. For this reason, NAA is the de facto industry standard for applications such as online conveyor belt analysers.

More recently, downhole assay solutions have entered the market, enabling elemental analysis from within a borehole (typically on bench or in grade-control drilling). This is where the larger measurement volume of NAA provides greatest value, sampling truly representative sample volumes. PFTNA-based logging tools package a pulsed neutron generator and an advanced gamma ray detector into a downhole assembly. These tools record the energies of characteristic gamma rays generated when fast neutrons undergo inelastic interactions with, and thermal neutrons are captured by, atomic nuclei in the formation around the tool. The efficiency of this downhole assay data collection allows high spatial (borehole) and vertical (depth) sampling and data delivered in a time frame that facilitates live updates of grade models; in addition to offering various other insights that fit the description of a *Multi-Use-Measurement*.

Existing downhole assay solutions use regression relationships derived from calibration data sets to directly link measured spectra to elemental composition (Charbucinski *et al*, 1986; Market *et al*, 2021). This interpolation methodology requires the development of extensive calibration data sets comprising conventionally assayed reference boreholes for each orebody that the technology is to be deployed on. Due to the variability inherent in any spectroscopic measurement system, the response of each tool requires individual calibration in each orebody, and full recalibration is required following any significant repairs to a tool that result in a change in spectral response.

An alternative approach, under development for mining applications, decouples the relationship between measured spectra and elemental composition (Hertzog *et al*, 1989; Radtke *et al*, 2012). Tool-dependent spectral processing considers the individual characteristics of each tool's spectral response, without linking it to a specific orebody, while a physics-based approach provides the link between tool response and elemental composition. This is facilitated by integration with additional formation properties such as bulk density and dry bulk density, porosity, and moisture content that can be evaluated by monitoring the evolution of the neutron and gamma ray populations over time during a measurement (Figure 2).

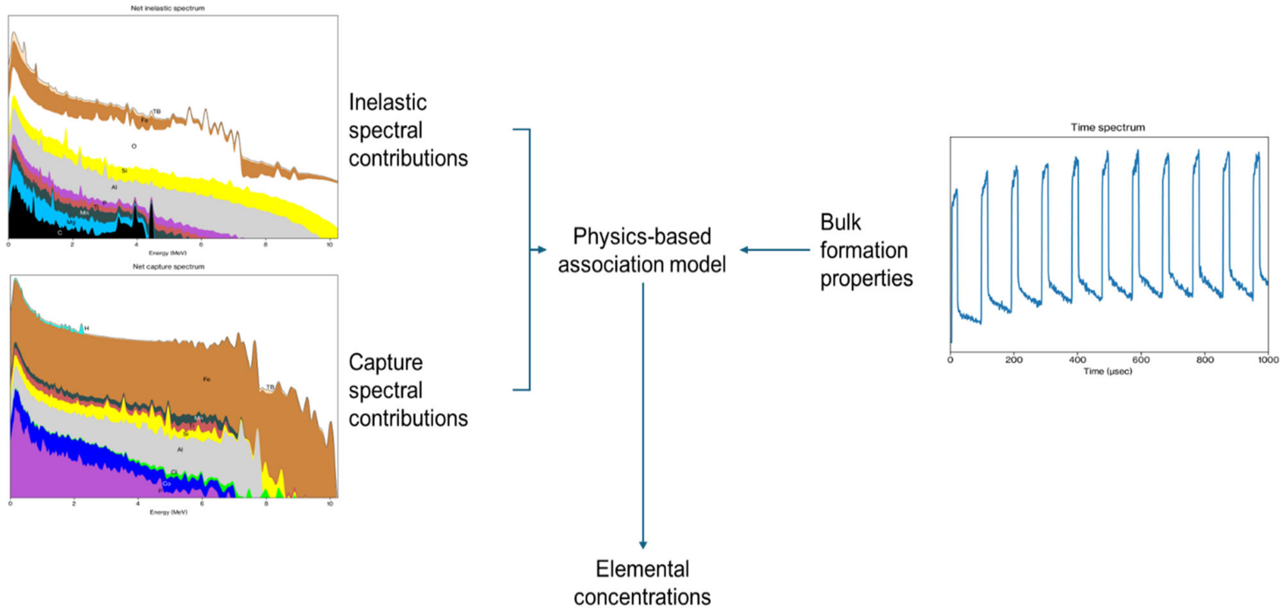


FIG 2 – Physics-based downhole assay processing workflow. Tool-specific gamma ray energy spectra are processed to derive tool-independent spectral contributions, that are then combined with bulk formation properties derived from time-dependent responses and a physics-based association model to quantify elemental concentrations.

This approach to downhole assay negates the need for tool-specific calibration or local calibration data sets, enabling meaningful data to be acquired from the first deployment of a tool at a particular deposit and fast swap of tools in an operational environment, as well as providing a route to incorporating this measurement into a *drilling-integrated measurement* workflow, greatly increasing the likelihood of this tool being applied by industry to its full potential.

Additionally, the significant volume of information generated during the measurement process makes downhole assay a *multi-use measurement* as it enables measurement or inference of numerous properties from a single measurement run, including:

- elemental composition
- bulk density and dry-bulk density
- porosity and moisture content
- automated mineralogy.

Knowledge of these parameters is integral to predicting and optimising downstream mine productivity.

THE WHEN – ACQUIRING, SURFACING AND CARRYING THE INFORMATION THROUGH THE VALUE CHAIN

As discussed in the previous section, the same data set can be of use to different stakeholders at different stages of the mine cycle. Using again the example of RHINO™, the same data may be used in quasi-real time by the driller in conjunction with MSE to monitor drill bit wear, before being uploaded to the cloud. They may then be used to create rock strength domains to help drill and blast engineers set their loading rules within a couple of hours. As UCS is correlated with mill performance indicators, this parameter can also be used to predict mill behaviour and improve comminution. Finally, RHINO™ data may be remobilised by geologists and geotechnicians weeks or months later to inform geological models.

Ensuring that the data are made available fast, but also remain easily accessible at later stages, helps maximise its use, which eventually drives business value.

This is articulated by delineating between data delivery, data collection and data curation.

Data delivery describes how quickly and seamlessly the data are transmitted to the decision-maker, whether based on-site or working remotely. With the advent of technologies such as Starlink, wi-fi-6 and 5G, the general improvement of drill-site or in-pit connectivity supports faster turn-around times. Mine sites with poor internet connectivity still require innovative work-around solutions such as preprocessing raw data on local Edge devices, thus allowing to deliver smaller processed data files rather than larger raw data archives. Integrated workflows also reduce the need for human intervention and therefore improve the data delivery time: for instance, at its early stages, the RHINO™ data delivery mechanism required processed results (axial delays or UCS) to be manually loaded into a dedicated software to delineate rock strength domains, which was a time-consuming process. Integrating RHINO™ with BlastIQ™ (on-bench blasting workflow management software) enables automated creation of the rock strength domain map, thus allowing drill and blast engineers to create loading rules in a timely manner (Figure 3).

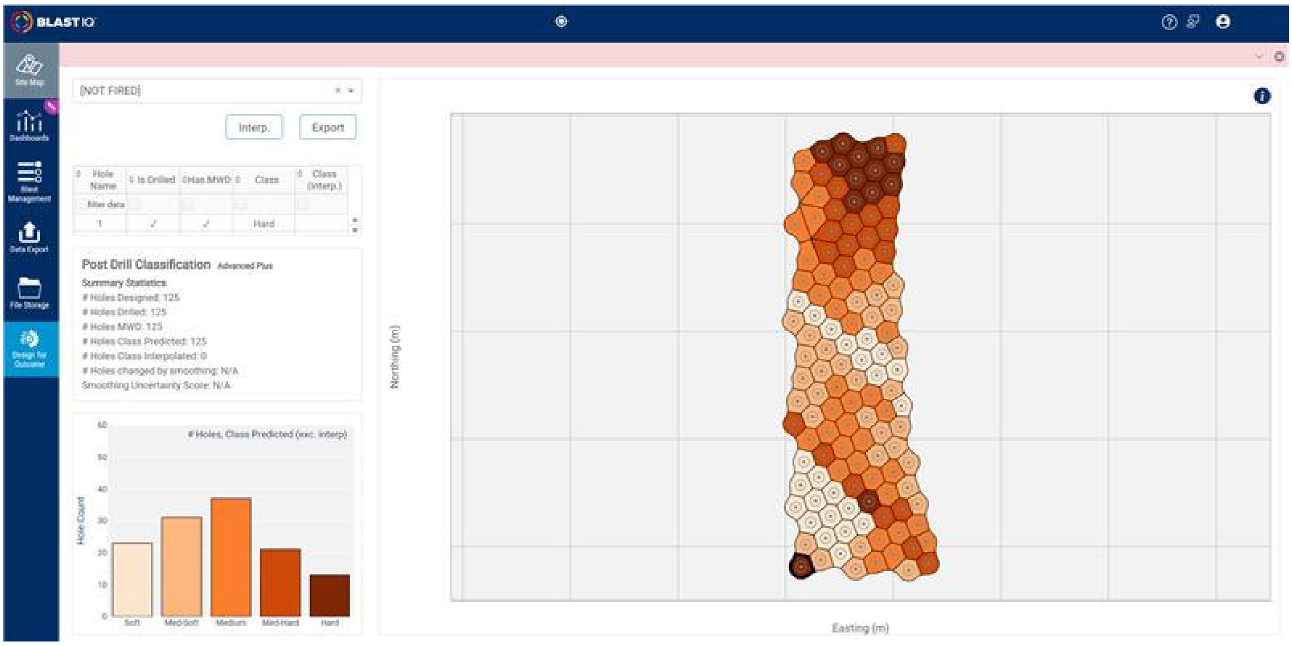


FIG 3 – Anonymised rock strength domain map generated from delivering RHINO™ data to partner application BlastIQ™, which serves different users and different needs.

Data collection describes how data are archived in the lakehouse and how easily they can be accessed at a later stage, both by internal and external users. Following a medallion architecture helps organise the data lake in different layers; ranging from a 'bronze' landing zone where raw data are uploaded, to a 'silver' layer where cleansed data are archived, all the way to a 'gold' layer where enriched, curated data and reports are stored and exposed. An agile access management system is required to ensure that stakeholders can retrieve the data when they need it.

Finally, **data curation** describes how a data set can be transformed, and integrated with data from other sources when such sources become available. Storing metadata and QC information along with the data help its remobilisation at a later stage.

It is time to consider how the equation can be changed to help this information be applied for maximum productivity improvements.

The opportunity for increasingly seamless integration of data from measurement acquisition devices through to drill plan management software, geology databases and beyond is implicitly suggested in the concept of a drilling-integrated-measurement workflow; but there is still a missing link that limits the data being used to its full potential downstream.

Quite simply, existing systems are good at collating data around material when it is *in situ* but are not so good at carrying the detailed information with the material as it starts moving through space and time: covering the operations of blasting, load and haul, stockpile management and beyond.

Surfacing Orebody knowledge into the growing body of digital optimisation tools at the time it is needed—*The When* of Orebody Characterisation—is the key to turning the data into process improvements and requires interactions between multiple applications.

Consider the data acquisition landscape described in this paper:

- Drilling-integrated survey equipment is used from exploration right through to grade control drilling to ensure a reliable geospatial map of the resource.
- UCS data from the drilling-integrated RHINO™ assembly is collected from grade control drilling through to blasthole drilling, integrated into the geological model and then tied to fragmentation data and mill performance data.
- Downhole assay is deployed in a workflow-integrated manner (either drilling-integrated or via automated deployment workflows) across grade control and blasthole drilling, to deliver high resolution grade information, including information about the presence and concentration of impurities, into the grade model in addition to rock density, moisture content, and mineralogy data into the geometallurgical model.

All these technologies exist or are in late-stage development, including associated deployment systems.

The missing piece is the next one—a data architecture built with modern, unattended integration points that links systems from Mine to Mill and that doesn't just push data along the chain, but continuously updates based on information from field measurements or models post blasting. The authors are aware of at least one group developing such a system and seeking to partner with other key players and expects first versions to hit the market in 2025.

Examples of the value deliverable from this modern technology stack are:

- Fragmentation on spec to optimise milling performance using blast design performed on data from the actual rock being blasted.
- Reduced dilution by integrating high-resolution assay data and optimised blast design with blast movement modelling to guide scheduling of trucks and shovels.
- Better blending by taking information gathered during load and haul such as shovel fragmentation data that tightly geolocates the material post-blast back into the model in real time, enabling information on grade and hardness to (virtually) move with the rocks.

Each of these initiatives represents a potential step change for workflows in the industry and has been proven at demonstration level but rarely sustained. Our opportunity is to change the equation and make these future possibilities our new global standard.

CONCLUSIONS

This paper reviewed how mine productivity can be improved by addressing the *Where*, *What* and *When* of orebody characterisation.

While stand-alone measurements can provide valuable information about the subsurface, combining them with other data sources often significantly enhances their value and helps inform decisions along the entire Mine to Mill value chain. To be analysed alongside other data sets, individual measurements need to be precisely geolocated (the *Where*). Deciding which properties to measure (the *What*) is also critical as some measurements may be multi-use, thus providing insights at different stages of the mine's life. In this paper, we covered the example of UCS, whose analysis can help optimise predictive maintenance, drill and blast outcomes, and even mill performance. Finally, delivering data in a timely manner to inform decisions (the *When*), and archiving them to be easily available and usable at later stages helps maximise the value that various stakeholders can extract from them.

We introduced the concept of drilling-integrated measurement workflows. Going beyond expert- and driller-operated measurements, drilling-integrated workflows tap into recent advances in connectivity to enable data acquisition without interrupting ongoing drilling operations. By not hindering the driller's productivity, this minimally invasive protocol supports measurement technology acceptance and uptake. Limiting the number of personnel in the pit also reduces the risks associated with coactivity. Finally, leveraging IoT solutions also enables remote QC and troubleshooting, thus improving overall data quality and reducing measurement downtime, while facilitating value extraction from the measurements and associated workflows.

As we have discussed in this paper, the technologies that can drive this next horizon of industry productivity improvements are already amongst us, but careful consideration of their deployment and integration is necessary if we want to see them applied to their full potential.

REFERENCES

Adesida, P A, 2021. Analysis of the Effect of Rock Properties on Extraction Haulage System Performance, *Ijird*, 10(5):166–171. https://doi.org/10.24940/ijird/2021/v10/i5/MAY21037

Charbucinski, J, Youl, S F, Eisler, P L and Borsaru, M, 1986. Prompt Neutron-Gamma Logging for Coal Ash in Water-Filled Boreholes, *Geophysics*, 51(5):1110–1118. https://doi.org/10.1190/1.1442165

Davis, F, 1989. Perceived Usefulness, Perceived Ease of Use and User Acceptance of Information Technology, *MIS Quarterly*, 13(3).

Dotto, M S and Pourrahimian, Y, 2018. Effects of Fragmentation Size Distribution on Truck-Shovel Productivity, University of Alberta Mining Optimisations Laboratory (MOL), Report 9.

Griffiths, R, Warden, S and Alonso, R, 2023. Rock Strength While Drilling Measurement Delivers Improved Mine Efficiency and Operational Savings, *Minexellence*.

Hertzog, R, Colson, L, Seeman, B, O'Brien, M, Scott, H, McKeon, D, Wraight, P, Grau, J, Ellis, D, Schweitzer, J and Herron, M, 1989. Geochemical Logging with Spectrometry Tools, *SPE Formation Evaluation*, 4(2):153–162, https://doi.org/10.2118/16792-pa

Hunter, J, 2024. Reliability and Accuracy Review – Champ Ori. Available from: <https://axisminetech.com/wp-content/uploads/2024/02/Axis-Champ-Orientation-Case-Study-2024-EN.pdf> [Accessed: 4 July 2024].

Isheyskiy, V and Sanchidrián, J A, 2020. Prospects of applying MWD Technology for Quality Management of Drilling and Blasting Operations at Mining Enterprises, *Minerals*, 10(10).

Market, J, Simpson, C, Rossiter, H and Jeanneau, P, 2021. Advanced in downhole Array Measurements and Calibration Techniques, Iron Ore Conference (The Australasian Institute of Mining and Metallurgy: Melbourne).

Nainggolan, D, Sitorus, R, Eveny, O and Sariandi, F, 2018. Correlation between uniaxial compressive strength (UCS) and blasting geometry on rock excavation at PT Agincourt resources, *IOP Conference Series: Earth and Environmental Science*, 212:012065. https://doi.org/10.1088/1755-1315/212/1/012065

Olaleye, B, 2010. Influence of some rock strength properties on jaw crusher performance in granite quarry, *Mining Science and Technology*, 20(2):204–208.

Radtke, R J, Lorente, M, Adolph, B, Berheide, M, Fricke, S, Grau, J, Herron, S, Horkowitz, J, Jorion, B, Madio, D, May, D, Miles, J, Perkins, L, Philip, O, Roscoe, B, Rose, D and Stoller, C, 2012. A New Capture and Inelastic Spectroscopy Tool Takes Geochemical Logging to the Next Level, SPWLA 53rd Annual Logging Symposium, paper AAA.

Segui, J and Higgins, M, 2002. Blast Design Using Measurement While Drilling Parameters, *Fragblast*, 6(3–4):287–299. https://doi.org/10.1076/frag.6.3.287.14052

Ultra-wide band based collision avoidance for underground mines

B Li[1], K Zhao[2] and H Gong[3]

1. Associate Professor, University of New South Wales, Sydney NSW 2033. Email: binghao.li@unsw.edu.au
2. Research Engineer, University of New South Wales, Sydney NSW 2033. Email: kai.zhao@unsw.edu.au
3. General Manager, Roobuck Pty Ltd, Sydney NSW 2100. Email: henryg@roobuck.com.au

INTRODUCTION

Health and safety are the first priority for Australian minerals sector. Australia has a global reputation in the mining industry. However, accidents occur every year. Legislation and regulation are important to prevent the accident from occurring, so do the new technologies. It is sad to witness the collision incident persisting and the long called collision avoidance system (CAS) is still not widely used in underground mines. The main reason is that the existing systems are still not advanced enough. The current CASs utilise GPS, infrared, ultrasonic, RFID, Radar, electromagnetic etc have their limitations and disadvantages. For instance, GPS is widely used in a surface mine, but it cannot be applied in underground mine; Infrared and electromagnetic have the false positive problem.

Ultra-Wideband (UWB) is a communications technology that employs a wide bandwidth (defined as greater than 20 per cent of the centre frequency or 500 MHz). 500 MHz bandwidth results in pulses of 0.16 ns width, which means that it is possible to do accurate ranging. The range measurement accuracy can be of the order of centimetres.

To achieve high accurate range measurement, the transmitter and receiver are required to be synchronised. However, to synchronise the devices is not an easy task no mater a wired or wireless method is used. To avoid the need for synchronisation, a technique for measuring the round-trip of the RF signal is normally used.

The principle of using UWB for collision avoidance is simple: we continuously measure the range between vehicles or vehicles and workers. If the range falls below a threshold (eg 10 metres), a warning is issued. However, the presence of multiple vehicles and/or workers poses a challenge in arranging range measurements between them. The research team at UNSW has developed a UWB-based CAS with the potential to comprehensively address the underground collision avoidance problem.

THE SYSTEM STRUCTURE

The system comprises UWB-enabled tags (cap lamps are the typical tags) for workers and Vstations for vehicles (refer to Figure 1). Each Vstation includes one or more UWB nodes and a control unit connecting the nodes via a CAN bus. Figure 1a shows a Vstation consisting of four UWB nodes and a control unit. The control unit coordinates the range measurements of the four UWB nodes with the nearby Vstations and tags and provides the warning information if the ranges is below a threshold. Figure 1b shows the UWB enabled cap lamp and Figure 1c displays a Vstation (with only one UWB node) exchange messages with a cap lamp nearby. A Vstation with one UWB node can define a round warning zone around it, ie if a tag is inside or outside the warning zone. With two UWB nodes, Vstation can tell if the tag is in front of, parallel to or behind the vehicle. With four or more UWB nodes, installed in the corner of the large vehicles, Vstation can pinpoint the tag's relative location and establish more accurate warnings. Using inputs from the vehicle's ODB2 port, the multiple nodes can be used to make the warning zone respond dynamically based on the vehicle's movements. The controller can generate warnings that take into account the vehicle's speed and direction.

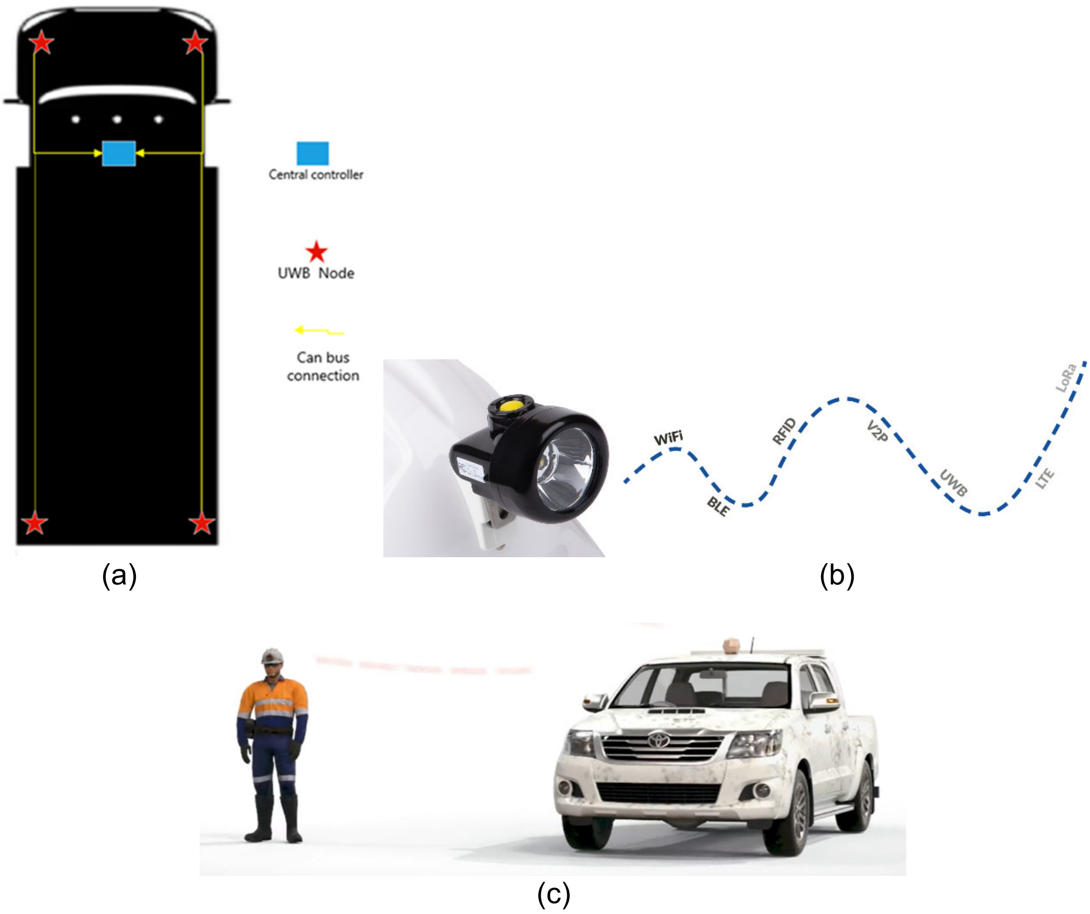


FIG 1 – UWB based collision avoidance system: (a) Vstation; (b) UWB enabled cap lamp; (c) Vstation and cap lamp exchange information.

THE PROTOCAL

As a Vstation need to communicate with the nearby Vstations and tags and measure the round-trip of the RF signal between a UWB node and a tag (or another node in different Vstation). Hence, a method is needed to arrange the time slot for each range measurement to avoid the signal collision. We have devised a sophisticated UWB ad hoc protocol to manage range measurements with high frequency.

In this protocol, we define the time frame which is a plan of the time-space usage for a time piece of 40–320 ms. It contains 4–16 time slots whose length can be 10–20 ms (refer to Figure 2). The time frames are only maintained by the initiators and only the initiators would occupy the time slots in the time frames. The responders only react to the ranging requests from the initiators. A time frame is created in an ad hoc mode which means it will be created when it is needed and be destroyed when there is no range measurements requirement (no collision risks). The time frame is denoted by a cycle as it will proceed repeatedly, ie when the last time slot ends, the first time slot starts again.

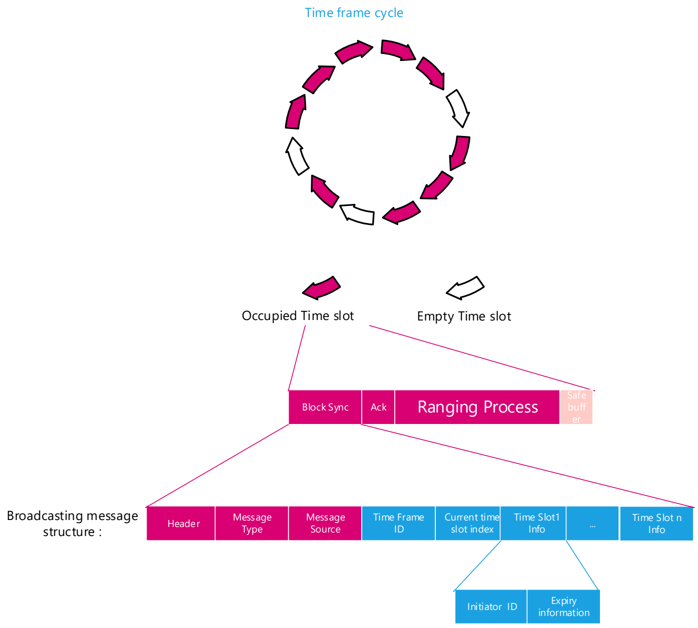


FIG 2 – Time frame for the ad hoc protocol.

The protocol can support up to four Vstations with four nodes each or eight Vstations with two nodes each. Every UWB nodes (of every vehicle) can perform the ranging process three times per second and up to 50 location calculations can be carried out per second.

The protocol is in the final stage of Patent Cooperation Treaty.

FUTURE WORK

The UWB based collision avoidance system is currently undergoing the commercialisation process.

Applications of multi-modal human activity recognition to enhance worker safety in underground mines

J Li[1], L Yao[2], B Li[3] and C Sammut[4]

1. PhD Candidate, University of New South Wales, Sydney NSW 2052.
   Email: jingcheng.li@unsw.edu.au
2. Senior Principal Research Scientist and Science Lead, CSIRO's Data61, Sydney NSW 2017.
   Email: lina.yao@data61.csiro.au
3. Associate Professor, University of New South Wales, Sydney NSW 2052.
   Email: binghao.li@unsw.edu.au
4. Professor, University of New South Wales, Sydney NSW 2052. Email: c.sammut@unsw.edu.au

INTRODUCTION

The underground mine environment is inherently complex and hazardous, which necessitates ensuring mining workers' safety. With the fast development of AI techniques, human activity recognition has become a crucial task to enhance daily life, especially in such challenging settings. This enables automatic monitoring and detection of the mine workers' activities and operations on a large scale, which leads to better support of workers' safety and welfare.

Existing traditional uni-modal approaches, which use data of one single modality, suffer from low data quality and noise, so they struggle to generalise effectively in such extreme conditions (Li *et al*, 2022). As underground mines have extreme and complicated environments, such as dust, low light, signal interference, and rugged terrain, uni-modal approaches could not resolve such obstacles and are not suitable for real-world deployment. Multi-modal human activity recognition approaches could use data from multi-modal sources, thus capturing complementary information and producing robust and effective performance in recognising and monitoring mining activities. In this case, designing suitable multi-sensor hardware and AI activity recognition models has become a pivotal task. Producing efficient multi-modal approaches for edge deployment is another problem worth exploring.

This abstract introduces and discusses the challenges and solutions of conducting human activity recognition in underground mine environments and proposes a Multi-task Multi-modal Transformer Network (MMTN) to resolve the human activity recognition task in a multi-modal scenario. The approach involves multi-modal data processing and utilising attention-based deep learning methods to extract the salient information, thus producing effective results along with robust generalisation ability. The knowledge obtained from this work provides insight into integrating and analysing multi-sensory data to recognise and monitor activity data, which would benefit maintaining workplace safety and operational efficiency in the underground mine environment.

METHOD

The MMTN is a multi-task learning-based transformer network to resolve the multi-modal human activity recognition task. Figure 1 shows the overall architecture of the MMTN model. The model consists of three components: a unified representation layer, a multi-modal spatial-temporal transformer module, and a multi-task learning module.

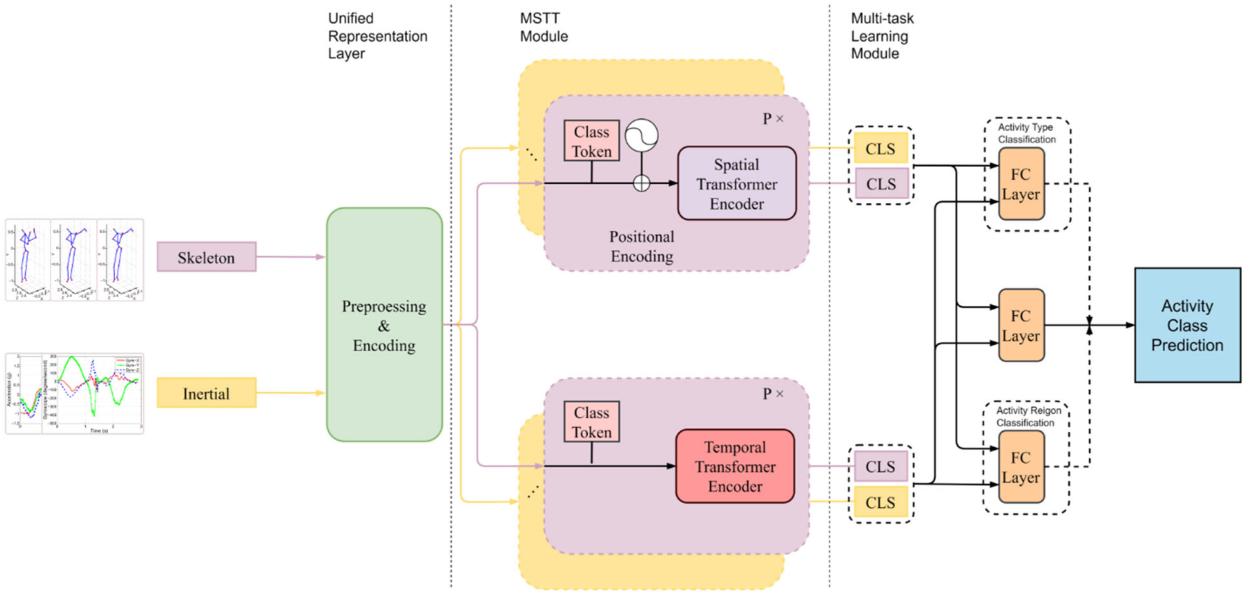


FIG 1 – The architecture of the MMTN model for the multi-modal human activity recognition task.

The unified representation layer. The multi-modal data may have different data representation structures. For example, the inertial data is 1D over time and with a frequency of 100 HZ, while the RGB data is in 3D and has a frequency of 24 fps. In this way, there is a need to transform the input data into a generalised representation for further feature extraction. We utilise the generalised encoding layer from our previous work MATN (Li *et al*, 2022), to conduct data preprocessing without introducing complex modality-specific feature encoding methods. Especially when in the underground mine environment, this would help to improve the efficiency of the model.

The multi-modal spatial-temporal transformer module. MMTN utilises the multi-modal spatial-temporal transformer (MSTT) module from the MATN model, to extract the salient spatial and temporal information from the input data. Unlike the LSTM network, which suffers from the long-range dependency problem, transformers can process the entire input sequence at once thus more effectively extracting the important relationships by applying the attention mechanism. While temporal information is crucial to produce the classifications, it is proven that the spatial domain, for example, body joints, may contain beneficial information to produce more effective and robust results.

The multi-task learning module. Instead of training the model on one single task, jointly training the model on multiple tasks may help leverage the complementary information as well as recognise the differences between the tasks. In this way, by adding extra constraints, the model can achieve improved accuracy and more importantly, produce more robust results. In this work, except the original activity classification task, two other sub-tasks are introduced, the activity region classification and the activity type classification. More specifically, the activity region classification task aims to determine whether the activity is primarily performed by the upper body or the lower body. The activity group classification task is designed to predict the type of the involved activity. In this case, we set three activity group types: gesture (swipe left, draw circle etc), daily activities (knock, clap etc), and sports (boxing, bowling etc). In the training process, the model is optimised by an overall loss, which is the weighted sum of the three tasks. In the testing step, the model generates the final activity class prediction. As the underground mine environment usually results in extreme conditions, such as data noise, weak light, and data loss, the multi-task learning module may help the model better generalise in such kind of environment.

RESULTS

To evaluate MMTN's performance, experiments were conducted on a public multimodal human activity recognition data set, UTDMHAD (Chen, Jafari and Kehtarnavaz, 2015). The UTD-MHAD data set contains 27 activities, where each activity is performed by eight subjects four times. After removing corrupted samples, the data set consists of 861 samples. A 50–50 subject evaluation method was used following the original paper's setting, where the odd-numbered subjects (1, 3, 5, 7) were used as the training set and the even-numbered subjects (2, 4, 6, 8) were used as the testing set. Top-1 accuracy was used as the evaluation metric. The overall results in Table 1 show that MMTN achieved competitive performance with an accuracy of 91.95 per cent using skeleton and inertial data, which is 5.42 per cent higher than Gimme Signal (Memmesheimer, Theisen and Paulus, 2020). In the meantime, introducing the multi-task learning module has improved the MMTN's performance by 1.02 per cent. This result demonstrates that by adding extra constraints, the multi-task learning module effectively improves the model's accuracy and robustness.

TABLE 1

Performance comparison on the UTD-MHAD data set. S: Skeleton, D: Depth, I: Inertial, aug: augmentation.

Method	Modality Combination	Accuracy (%)
UTDMHAD	D	66.1
UTDMHAD	I	67.20
UTDMHAD	I + D	79.10
Gimme Signals	I + S	76.13
Gimme Signals	I + S (aug)	86.53
MMTN (without multi-task)	I + S	90.93
MMTN	I + S	**91.95**

CONCLUSION

This abstract introduces MMTN, a multi-task learning-based transformer network, which underscores the necessity and effectiveness of multimodal human activity recognition approaches in underground mines, emphasising their critical role in ensuring safety and operational efficiency. This work not only addresses the unique challenges of underground mine environments but also paves the way for advanced human-computer collaboration in industrial settings. In the future, it is important to construct multimodal human activity recognition data sets in an underground mine environment to help improve the model's robustness thus meeting the industrial needs.

ACKNOWLEDGEMENTS

This work was supported by the Cooperative Research Centres Projects (CRCP) Grants 'DeepIoT' project.

REFERENCES

Chen, C, Jafari, R and Kehtarnavaz, N, 2015. UTD-MHAD: A multimodal dataset for human action recognition utilizing a depth camera and a wearable inertial sensor, in *2015 IEEE International Conference on Image Processing (ICIP),* pp 168–172.

Li, J, Yao, L, Li, B, Wang, X and Sammut, C, 2022. Multi-agent Transformer Networks for Multimodal Human Activity Recognition, in *Proceedings of the International Conference on Information and Knowledge Management*, pp 1135–1145.

Memmesheimer, R, Theisen, N and Paulus, D, 2020. Gimme Signals: Discriminative signal encoding for multimodal activity recognition, arXiv. https://doi.org/10.48550/arXiv.2003.06156.

Enhancing the fairness in LoRa-Based linear wireless mesh networks in underground mining

Y Li[1], N Udugampola[2], X Ai[3], B Li[4] and A Seneviratne[5]

1. Undergraduate, UNSW, Sydney NSW 2052. Email: yikun.li@student.unsw.edu.au
2. Postgraduate Researcher, UNSW, Sydney NSW 2052. Email: n.udugampola@unsw.edu.au
3. Postdoctoral Fellow, UNSW, Sydney NSW 2052. Email: x.ai@unsw.edu.au
4. Associate Professor, UNSW, Sydney NSW 2052. Email: binghao.li@unsw.edu.au
5. Professor, UNSW, Sydney NSW 2052. Email: a.seneviratne@unsw.edu.au

ABSTRACT

LoRa (Long Range) is a low-power, long-range wireless communication technology that has gained significant research interest for its potential use in multi-hop linear wireless sensor networks (LWSNs) for underground mines. These networks deploy LoRa-enabled sensor nodes in underground mines, together with LoRa repeaters placed along mine tunnels to relay sensor data to a LoRa gateway, which connects to a backend network for application-level processing. Since the packets generated by sensor nodes farthest from the gateway have to hop through many repeaters, their probability of successfully reaching the gateway is significantly lower due to the higher chance of packet collisions compared to sensor nodes closer to the gateway, resulting in a lack of network fairness for the sensor nodes. In this paper, we first present an algorithm to improve the fairness of a LoRa LWSN by grouping neighbouring nodes and adjusting the number of packet re-transmissions and transmission intervals for each group. Then, we demonstrate that the fairness of a simulated LoRa LWSN can be improved by approximately 500 per cent by applying our algorithm. We verify our algorithm with network simulations under different network traffic levels and grouping strategies, obtaining fairness improvements in each scenario. Our algorithm and results will pave the way towards developing highly fair LWSNs for underground mining applications.

INTRODUCTION

LoRa (Long Range) technology is emerging as a significant component in the mining industry for establishing wireless sensor networks due to its low-power and long-range communication capabilities. LoRa is commonly utilised in LoRaWAN, a single-hop network protocol for long-range, low-power communication for IoT devices using a star topology. Compared to LoRaWAN, LoRa-based multi-hop and mesh networks offer more complex yet robust communication solutions with extended range (Centelles *et al*, 2021). Among these, LoRa-based LWSNs are particularly suitable for underground mines, where LoRa repeaters are placed along mine tunnels in a linear or sequential manner to relay data packets generated by LoRa-enabled nodes deployed in the mines to a LoRa gateway in a multi-hop approach (Branch and Cricenti, 2020).

In a research article, Branch, Li and Zhao (2020) presented a LoRa-based multi-hop LWSN designed for emergency use in underground mines, aiming to gather location data from LoRa-enabled tags carried by individuals and equipment within the mine. They evaluated the fairness of a network — specifically, whether nodes deployed at different locations have an equal chance of successfully delivering packets to a LoRa gateway— with the network having ten LoRa repeaters and uniformly distributed LoRa-enabled tags, while varying the network traffic load. Their network performs poorly with very low packet delivery rates and significant unfairness under high network traffic. As a result, miners deeper within the mine may experience reduced chances of communication with the gateway or the mine's control centre, posing a substantial safety concern within their network.

Due to the low data rate in LoRa, the network bandwidth is highly limited, making it unfeasible to implement complex network protocols that involve the exchange of control and acknowledgement messages between the sensor nodes and the gateway. Simple message broadcasting algorithms, featuring randomised repeater waiting periods to avoid LoRa packet collisions, are predominantly used (Beltramelli *et al*, 2021), but they suffer heavily from a lack of network fairness because packets generated by sensor nodes farthest from the gateway must hop through many repeaters, making their probability of successfully reaching the gateway, significantly lower compared to the nodes closer to the gateway.

In the next section, we will investigate this fairness issue and propose an algorithm to make the network fairer by equalising the packet delivery ratios of individual LoRa nodes deployed throughout the network.

METHODOLOGY

Simulation set-up

A LoRa mesh network simulation platform developed by us, called LoRaMeshSim, was used to simulate the network introduced by Branch, Li and Zhao (2020) and replicate the performance data they presented. The same simulation platform was utilised to test our fairness algorithm.

The simulated network is a simple multi-hop LoRa network, consisting of ten repeaters arranged linearly in a way that each repeater's transmission only reaches its adjacent repeaters. A LoRa node (end device) is placed near each repeater, intermittently transmitting packets at uniformly distributed random time intervals, with a mean of 10 mins, and with just enough power to reach only its corresponding repeater. Figure 1 illustrates the path a packet originating from the node near the Repeater 10 should traverse to reach the LoRa gateway. In the figure, nodes are denoted in blue, repeaters in green, and the gateway in red.

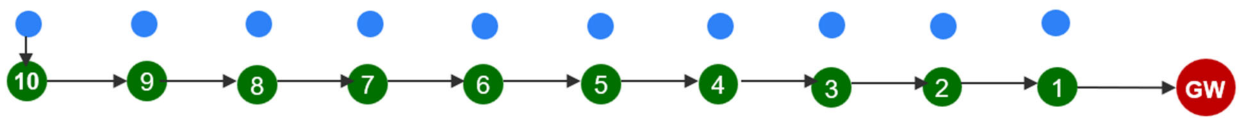


FIG 1 – The simulated LoRa network. The distance between the gateway (GW) and Repeater 10 can be up to 10 km for the LoRa parameters adopted in the simulator.

In this network, all LoRa transmissions were conducted using the same frequency channel (918 MHz), bandwidth (125 kHz), and spreading factor (SF=12). A simple repeater algorithm was employed, designed so that upon receiving a new packet, the repeater waits for a random period and then retransmits the packet.

Firstly, we simulated the described network as it is, with the original implementation presented by Branch, Li and Zhao (2020). Next, we simulated the same network with the same level of traffic, and with our fairness algorithm applied. As shown in Figure 2, we could observe a significant improvement in network fairness after applying the algorithm.

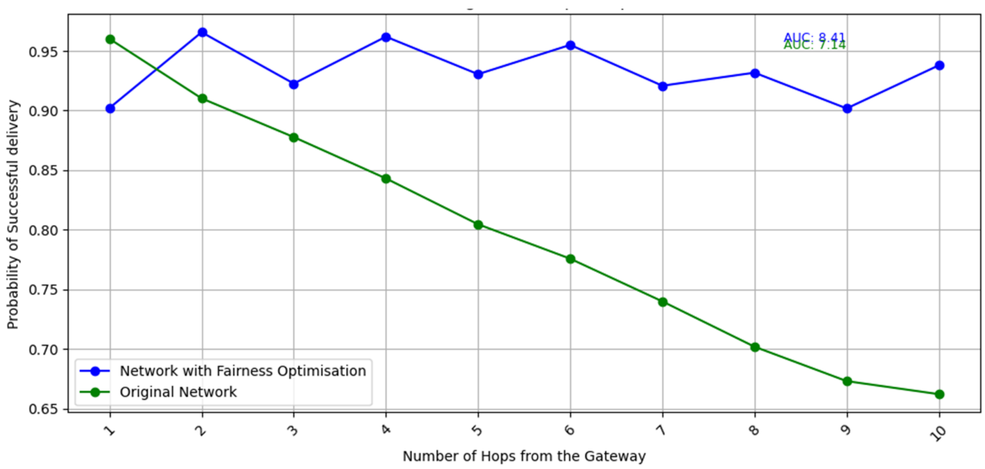


FIG 2 – Individual packet delivery probabilities of sensor nodes with and without fairness algorithm.

Fairness algorithm

This algorithm provides a fairer opportunity for nodes located farther from the gateway by enabling unfairly treated nodes to repeat the same data in multiple packets sent within the same time interval as before. For instance, if the node at Repeater 10 of the network illustrated in Figure 1, sends the same data payload six times in six separate packets, its packet transmission frequency is increased sixfold to maintain the same effective data rate as before. The number of packets with the same data payload, repeated by a sensor node can be defined as repeat ratio.

In this algorithm, we divide the nodes into multiple groups based on their distance from the gateway in terms of the number of repeaters. Then we assign how many times nodes in each group should repeat the same data in multiple packets.

Experiments

Application of the fairness algorithm

For the proposed fairness algorithm applied to the network depicted in Figure 1, the repeat ratio for each node is provided in Table 1. Here the nodes are divided into six groups. In this case, the nearest node at Repeater 1 will only send the message once in 10 mins just like in the original network, before applying the algorithm.

TABLE 1

Data repetition times of nodes at each number of hops from the gateway (nodes are divided into six groups for all these networks with different loads).

Number of hops from the gateway to the sensor node	1	2	3	4	5	6	7	8	9	10
Repeat ratio	1	2	2	3	3	4	4	5	5	6

Testing with different number of node groups

Four configurations were tested to assess the impact of node groupings in this algorithm on network fairness: 1 group, 2 groups, 3 groups, and 4 groups.

- **1 Group**: All nodes have the same repeat ratio.
- **2 Groups**: Nodes are divided into two groups. The group farther from the gateway has a repeat ratio of 2, while the group closer to the gateway has a repeat ratio of 1.
- **3 Groups**: Nodes are divided into three groups. The farthest group has a repeat ratio of 3, the middle group has a repeat ratio of 2, and the nearest group has a repeat ratio of 1.
- **4 Groups**: Nodes are divided into four groups with repeat ratios of 4, 3, 2, and 1 from the farthest to the nearest group, respectively.

All four network configurations involved the same number of nodes and repeaters as in the original set-up. All LoRa transmissions were conducted using the same frequency channel (918 MHz), bandwidth (125 kHz), and spreading factor (SF=12). Each LoRa node transmits packets in uniformly distributed random time intervals with a mean of 10 mins. The only change made was the repeat ratio for different groups of nodes.

Testing under different network loads

In the previous experiment, regardless of the repeat ratios, each sensor node transmitted a new data payload approximately every 10 mins. In this experiment, all simulated networks utilise six node groups, but the data rate of nodes is varied to increment the network traffic load.

In this experiment, four network traffic levels (aka network loads) were tested. Under the lowest network load, each sensor node sends a new data payload approximately every 60 secs. Then the network load was gradually increased by decreasing this time interval to 40 secs, 20 secs, and

10 secs. Therefore, the network configuration with each node sending new data payloads every 10 secs, resulted in the highest network load.

The same network layout as in Figure 1 was utilised. Since the nodes are divided into six groups for all these networks with different loads, the repeat ratios for the nodes are as in Table 1. All network configurations and LoRa parameters remained the same except for the network load.

RESULTS

Results for the application of the fairness algorithm

The simulation results for the network illustrated in Figure 1 are presented in Figure 2. The green curve illustrates the individual probability of packet delivery for each node, as implemented by Branch, Li and Zhao (2020). The blue curve illustrates those individual probabilities after applying our fairness algorithm to the same network as the green one, indicating improved fairness across the network after applying the algorithm. As observed in Figure 2, in the network implementing the fairness algorithm, data from nodes farther from the gateway have a comparably high likelihood of successful transmission as those closer to the gateway.

The range and variance in the distribution of individual packet success probabilities of the nodes can be considered indicators of network fairness (Buzna and Carvalho, 2017). The range is the difference between the highest and lowest packet success probabilities, while the variance indicates the deviation of the individual probabilities from their average. Therefore, the lower the range or the lower the variance, the higher the network fairness.

According to Figure 2, the range of the individual packet success probabilities is 0.064 in the network implementing the fairness algorithm, which is approximately 21 per cent of the range in the original network, which is 0.298. Since the range has become five times lesser after applying the fairness algorithm, we can conclude that our algorithm has increased the fairness of the network by approximately 500 per cent in this scenario. Besides, the variance of the individual packet success probabilities decreased from 0.122 to 0.023 after applying the fairness algorithm, which demonstrates an improved consistency of these individual packet success probabilities across the entire network.

We can assign a quantitative value to indicate the fairness of a network as follows:

$$Network\ Fairness = \frac{1}{Range\ of\ individual\ packet\ delivery\ probabilities\ of\ the\ nodes}$$

Results of testing with different number of node groups

Here, we simulated the same network as in Figure 1, increasing the number of node groups as described previously. The distributions of the individual packet delivery probabilities for the four tested grouping strategies are plotted in Figure 3. This figure demonstrates that increasing the number of groups in our algorithm improves fairness in the network, with fairness values of 2.86, 4.0, 5.0, and 6.67 corresponding to the increased number of groups. The lowest range can be observed in the plot for the ‘4-group’ strategy, thereby resulting in the highest network fairness. This is because grouping allows the network to have a more balanced load distribution based on the number of hops each node is away from the gateway. This enhancement in fairness ensures nodes farther from the gateway have a better chance of successful transmission, making the network more robust, equitable, and crucial for safety and operational efficiency.

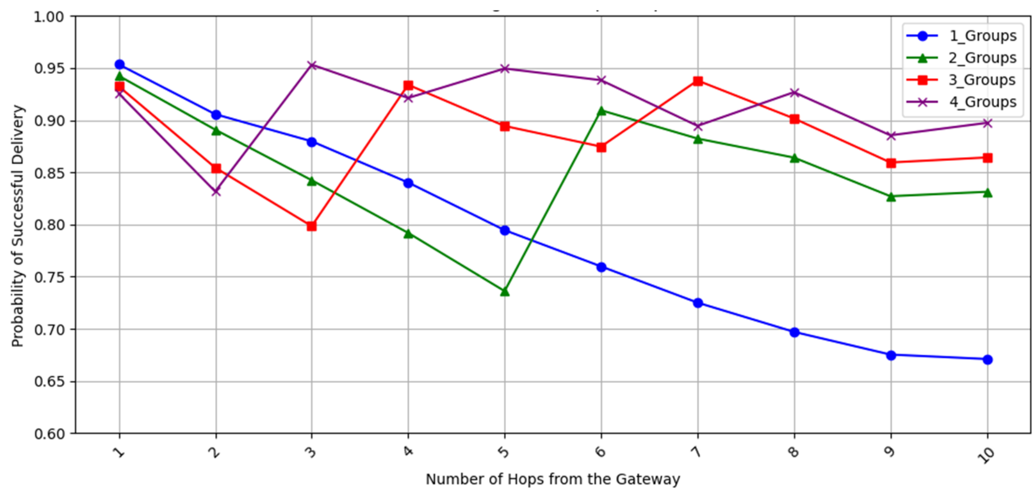


FIG 3 – Individual packet delivery probabilities for different node groupings.

Results of testing under different network loads

In this experiment, we evaluated the fairness improvements of the network under four different network loads as described previously. Figure 4 illustrates the distributions of individual packet delivery probabilities for the four network loads without applying the fairness algorithm to the network. Figure 5 shows the same data after applying the fairness algorithm.

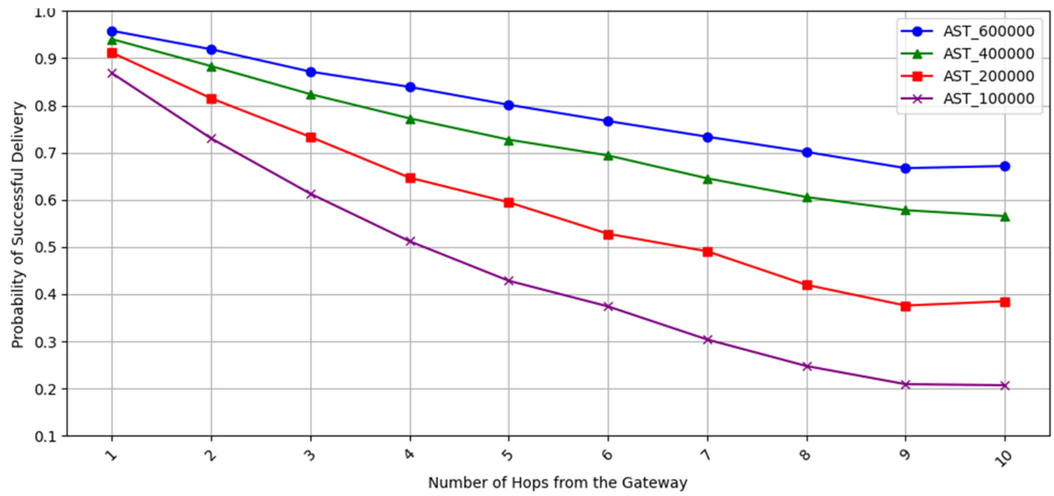


FIG 4 – Individual packet delivery probabilities in the original network without fairness algorithm under different network loads (AST – Average packet sending time interval of a node in milliseconds).

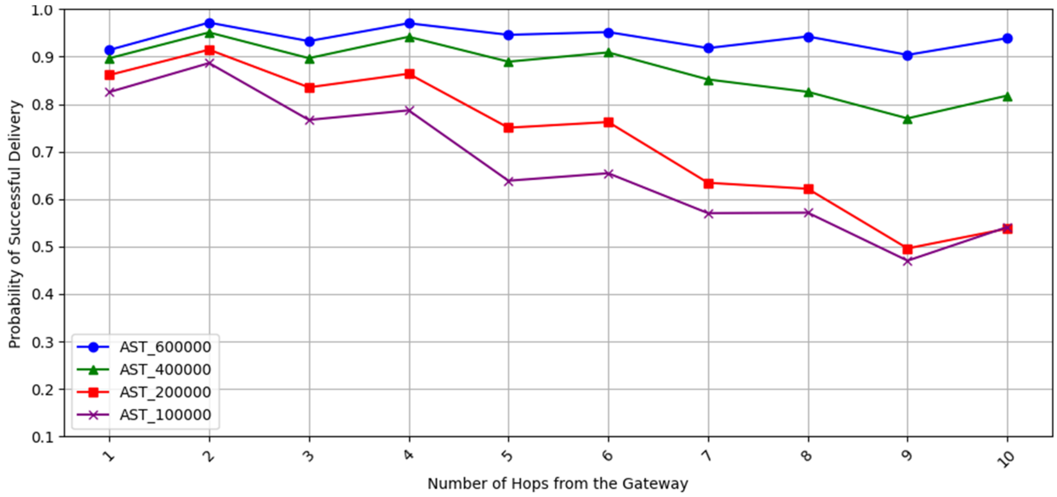


FIG 5 – Individual packet delivery probabilities after applying the fairness algorithm under different network loads (AST – Average packet sending time interval of a node in milliseconds).

In Figure 4, we can observe that increasing network load leads to increased packet congestion with lower packet success rates, which also degrades the fairness of the network without our algorithm. When increasing load the fairness values decreased as 3.7, 2.7, 1.9, and 1.5. Figure 5 demonstrates that the fairness algorithm is effective under different network loads. Here, when increasing the load the fairness values decreased as 14.7, 5.5, 2.4, and 2.4.

However, the enhancement of fairness in networks experiencing high traffic loads is less significant compared to those with lower traffic loads. This is because fairness degradation due to high packet congestion and collisions becomes pronounced, and attempting to have farther nodes repeat packets with higher repeat ratios escalates this issue with having more packets added to the network. Still, there is a significant improvement in the network fairness and the overall packet success rate of the network after applying our algorithm to a network with a high traffic load.

Consequently, our algorithm can enhance network fairness under various network loads both low and high. For highly congested networks, further optimisation or alternative approaches might be necessary to maintain fairness without exacerbating congestion.

CONCLUSIONS

In LWSNs that are typically used in underground mines, fairness plays a pivotal role in ensuring that all nodes have equal opportunities for effective communication with the gateway. However, due to the absence of collision-avoiding mechanisms, traffic originating from nodes farther from the gateway faces a higher likelihood of being dropped compared to nodes nearer the gateway, as these packets must hop through multiple LoRa repeaters. In this paper, we introduced an algorithm designed to address this issue by having farther nodes transmit the same data in multiple packets, thereby increasing their chances of successfully reaching the gateway.

The proposed fairness algorithm works as expected under different node grouping techniques and varying network loads. The algorithm improves fairness across different network loads, but its effectiveness decreases in highly congested networks. This fairness-enhancing algorithm ensures more equitable information can be delivered successfully, enhancing reliability and performance in critical environments.

Future research directions include developing a mathematical model to tune the repeat ratios to optimise the network fairness with the least number of repeated packets, investigating alternative methods to manage fairness in highly congested networks, and exploring variations in transmission power, utilisation of multiple frequency channels, and spreading factors to further improve network performance and fairness. This integration provides a comprehensive understanding of the experiments and their implications for enhancing fairness in LoRa-based Linear Wireless Mesh Networks.

ACKNOWLEDGEMENTS

This work is supported by the Cooperative Research Centres Projects (CRC-P) Grants under the project 'Underground mine LoRa network for monitoring/control/backup/rescue/robotics'.

REFERENCES

Beltramelli, L, Mahmood, A, Osterberg, P and Gidlund, M, 2021. LoRa beyond ALOHA: An Investigation of Alternative Random Access Protocols, *IEEE Transactions on Industrial Informatics*, 17(5).

Branch, P and Cricenti, T, 2020. A LoRa relay based system for detonating explosives in underground mines, Proceedings of the IEEE International Conference on Industrial Technology.

Branch, P, Li, B and Zhao, K, 2020. A LoRa-Based Linear Sensor Network for Location Data in Underground Mining, *telecom*, 1(2):68–79.

Buzna, L and Carvalho, R, 2017. Controlling congestion on complex networks: Fairness, efficiency and network structure, *Scientific Reports*, 7(1).

Centelles, R P, Freitag, F, Meseguer, R and Navarro, L, 2021. Beyond the Star of Stars: An Introduction to Multihop and Mesh for LoRa and LoRaWAN, *IEEE Pervasive Computing*, 20(2).

Enhancing geoscience model confidence via digital twins – integrated modelling, simulation, and machine learning technologies

M Liang[1], C Putzmann[2] and D Gokaydin[3]

1. Industry Process Consultant Senior Specialist, Dassault Systemes – GEOVIA, Brisbane Qld 4000. Email: min.liang@3ds.com
2. RnD Quality Engineering Manager, Dassault Systemes – GEOVIA R&D, Brisbane Qld 4000. Email: carl.putzmann@3ds.com
3. RnD Data Scientist Manager, Dassault Systemes – GEOVIA R&D, Brisbane Qld 4000. Email: dinis.gokaydin@3ds.com

INTRODUCTION

The mining industry faces numerous challenges in swiftly evaluating and exploiting new mineral deposits to meet the escalating demand for critical minerals and metals. These challenges necessitate the adoption of innovative techniques and technologies to expedite development cycles and facilitate the efficient exchange of knowledge and expertise. Traditional mineral exploration methods rely heavily on data governance, visualisation tools, and expert interpretation skills, often operating in isolation and limiting the integration of valuable data and knowledge (Lindsay and Perrouty, 2019). To address these integration challenges and bridge the industry's knowledge gap, the concept of a digital twin offers a holistic solution (Ahn, 2021; Nagovitsyn and Stepacheva, 2021).

DIGITAL TWIN ON CLOUD

This research highlights the pivotal role of a fully integrated geological modelling solution within a digital twin environment. Using a unified cloud platform for geological modelling, machine learning and testing multiple concurrent parameterised hypotheses allows the user to be able to generate multiple geological models in parallel using a cloud service approach. Using model comparison tools to ascertain differences between these models is critical. By integrating cutting-edge technologies and ensuring the traceability and adjustability of the digital life cycle of models, this geological modelling tool operates within a unified platform. Leveraging cloud-based applications for collaborative agility, process automation for speed, machine learning for pattern recognition to enhance knowledge of deposit behaviour under uncertain conditions, and simulation to test hypotheses, this integrated approach reduces decision latency and increases confidence in geological interpretation empowering geologists and engineers to utilise the best model for their purposes in real time.

MACHINE LEARNING IN GEOSCIENCE DATA EXPLORATION

One aspect of this integrated approach involves harnessing machine learning (ML) techniques for analysing geoscience data. Demonstrating this capability, we present an example utilising geophysical data to predict lithology and coal quality in a coalmine. Current techniques require a trained geologist to identify the lithology of different sections of a drill core, as well as structural features like faults, a time-consuming process (Stevens, 2010). In addition, selected regions of the cores are sent for laboratory geochemical analysis, further adding to the time and cost of processing drill core information. Ultimately, this means that assessing lithology and quality in drill cores acts as a bottleneck slowing down the pipeline leading to resource estimation. However, concomitantly with lithology and quality sampling, geophysical wireline data is also collected which is not only quicker and less expensive to gather, but is expected to be strongly correlated to both lithology and quality. Our platform includes ML models with the capacity to make predictions about lithology and quality, and for a side-by-side comparison to be made with human-generated lithology, and laboratory results. Once the model is trained in a subset of the data it can be used to make predictions about the remaining data, based solely on wireline data; once model predictions are reviewed by a geologist the model can be re-trained on all the data, closing the loop. This feedback between model and specialist knowledge not only leads to a better model, but may also help identify some errors in the original labelling, as any areas of discrepancy can be readily identified in the digital platform. Finally, the benefits extend beyond prediction accuracy and processing speed; they encompass the creation of a digital twin facilitating knowledge sharing across departments, result review, and approval.

IMPLICIT ALGORITHM FOR GEOLOGY MODEL

The Implicit Algorithm for Geology Model stands as a pivotal component, operating on a principle of indirect inference to construct geological models (Cowan *et al*, 2003). This algorithm facilitates borehole interpretation and the design of parametric geology models, fostering the generation of multiple hypotheses concerning the underlying geological structures. By drawing upon multiple versions of data stored centrally on a cloud platform, this approach empowers the exploration of diverse scenarios. A demonstration utilising drill hole data from a coalmine exemplifies how the model dynamically integrates AI/ML predictions on geology, enabling the testing of multiple hypotheses with enhanced precision. The engine driving this model creation allows users to quickly generate models on the cloud without the need for local hardware computations.

RESOURCE MODELLING WITH MACHINE LEARNING INTEGRATION

Resource modelling in mining operations traditionally relies on costly and time-consuming core drilling to obtain coal quality data. However, non-core drill holes, which are more abundant and contain wireline geophysical information, present an opportunity for leveraging ML techniques to predict coal quality. By harnessing ML predictions derived from non-core drill data, we integrate these insights into the resource modelling process. Employing advanced multivariate geostatistical techniques such as Adaptive Inverse Distance Weighting (Liang and Maxwell, 2021) or Co-kriging (Chilès and Delfiner, 1999), we incorporate ML-predicted data as an auxiliary variable in coal quality estimation. This integration offers significant benefits. Firstly, it enhances the confidence of the resource model by integrating ML-predicted data from wireline geophysical information, resulting in more reliable estimates of coal quality. Additionally, in regions with limited core hole coverage, our approach mitigates uncertainty by leveraging ML predictions, leading to more accurate assessments of resource potential in these areas.

Furthermore, by minimising the need for extensive core drilling through the use of ML techniques, we optimise resource estimation accuracy while effectively managing drilling costs. This comprehensive approach represents a significant advancement in resource modelling, offering mining operations enhanced efficiency, precision, and cost-effectiveness.

CONCLUSION

In conclusion, the adoption of a platform environment with modelling and simulation capabilities, alongside the use of digital twins and machine learning, offers significant benefits to the mining industry. By addressing integration challenges, enhancing knowledge sharing, and improving decision-making processes, this integrated approach holds great potential for optimising exploration and resource estimation endeavours in the mining sector.

REFERENCES

Ahn, E Y, 2021. Analysis of digital twin technology trends related to geoscience and mineral resources after the Korean new deal policy in 2020, *Economic and Environmental Geology*, 54(6):659–670.

Chilès, J-P and Delfiner, P, 1999. *Geostatistics: Modeling spatial uncertainty*, 695 p (Wiley: New York).

Cowan, E J, Beatson, R K, Ross, H J, Fright, W R, McLennan, T J, Evans, T R, Carr, J C, Lane, R G, Bright, D V, Gillman, A J, Oshust P A and Titley M, 2003. Practical Implicit Geological Modelling, in *Proceedings of the 5th International Mining Geology Conference*, pp 89–99 (Australasian Institute of Mining and Metallurgy: Melbourne).

Liang, M and Maxwell, K, 2021. Exploration cost reduction in a coal mine utilising Machine Learning predicted data, 2021 Bowen Basin Symposium.

Lindsay, M and Perrouty, S, 2019. Integrating geological data: Strategies for effective exploration, *Geological Society, London, Special Publications*, 492(1):1–14.

Nagovitsyn, O V and Stepacheva, A V, 2021. Digital twin of solid mineral deposit, *Journal of Mining Science*, 57(6):1033–1040.

Stevens, R D, 2010. Mineral Exploration and Mining Essentials, Pakawau GeoManagement.

Data-driven visualisation for the development of mining digital twin

R Liang[1], C Zhang[2], B Li[2], S Saydam[2] and I Canbulat[2]

1. The School of Minerals and Energy Resources Engineering, UNSW, Sydney NSW 2052. Email: ruiyu.liang@unsw.edu.au
2. The School of Minerals and Energy Resources Engineering, UNSW, Sydney NSW 2052.

ABSTRACT

The integration of digital twins in mining represents a significant advancement towards enhancing operational efficiency and decision-making. Central to this development is the role of visualisation, a crucial element in mining digitalisation. This paper aims to develop a data-driven visualisation solution for the construction of mining digital twins, highlighting how this innovation revolutionises the representation of physical mining environments. It spotlights the shortcomings of conventional visualisation methods, particularly their inability to accurately depict complex underground environments and their predominantly historical orientation. To address these challenges, this paper proposes a novel, data-driven approach. This approach extensively utilises CAD files, encompassing data from geological surveys to intricate mine plans, thereby significantly elevating the precision of digital twins. It supports real-time updates and enables flexible interaction with a variety of data types. Moreover, it introduces a comprehensive data diagram alongside the adaptation of a 3D tile index. This strategy ensures the efficient rendering of extensive mining environments, allowing for a more dynamic and interactive digital twin model. In conclusion, the implementation of data-driven visualisation in the construction of mining digital twins marks a pivotal advancement in the industry's digital transformation. It promises a more detailed, accurate, and dynamic depiction of mining operations.

INTRODUCTION

In the rapidly evolving field of mining engineering, the implementation of digital twins and the digitalisation of mining processes have become pivotal. At the heart of these advancements, visualisation lies the crucial role. Visualisation serves as a fundamental tool in comprehending and managing underground mining operations (Boschert and Rosen, 2016; Cameron, Waaler and Komulainen, 2018; Barnewold and Lottermoser, 2020; Duarte, Fernanda Rodrigues and Baptista, 2020; Lu *et al*, 2020; Elbazi *et al*, 2022). It can provide virtual duplicates for demonstrating data from diverse mining operations over time, enhancing understanding of the mine plan, communicating complex information of mining operations, facilitating decision-making, and validating and verifying the design across the entire mining scope (Cui, 2019; Liang *et al*, 2019; Sacha *et al*, 2019; Boje *et al*, 2020; Ltifi, Kolski and Ayed, 2020; Liang *et al*, 2023). Therefore, the objectives of visualisation can encompass various engineering drawings from different mining sections, in which the two-dimensional computer-aided-design (2D CAD) drawings are the extensively exploited resource for current mine planning (Xie and Lu, 2017; Lu *et al*, 2020; Li *et al*, 2021). Due to the complex geological conditions while implementing exploration and excavation in underground space, 2D CAD files by different layers/levels are still the main objective. While 3D modelling software and 3D CAD have been developed, it is still challenging to handle all mine plan layers and complex 3D geostructures in one singleton CAD or 3D CAD file, due to the large amount of entities (Sun, Lu and Tian, 2009; Xie and Lu, 2017; Zhu *et al*, 2018; Liang *et al*, 2019). Hence, 2D drawings are still the main communication medium, because of their good performance in processing drawings layer by layer. According to the current visualisation development in mining engineering, to precisely reflect the mining environment, 3D visual models are all generated manually based on 2D CAD files (Liang *et al*, 2018, 2019; Lu *et al*, 2020; Sishi and Telukdarie, 2020; Wong *et al*, 2020; Beckett, 2022). This manually work limits the real-time capability in visualisation applications, resulting in historical orientation and latency of updates and upgrades for mining visualisation systems. On the other hand, since most of the mining workings are constructed by blasting and machine excavating, the shape and outline cannot be as standard as building entities. The unpredicted and irregular contours hinder the automation progress of 3D model generation.

As a result, this paper aims to propose an automated data-driven strategy for the development of 3D visual models in underground mining to address these challenges. The proposed solution enables real-time 3D mine plan updates and provides lifetime support for the visualisation system. It could be a preliminary step for the development of mining digital twin systems. The main tasks of this paper are to identify CAD file-based drawing issues in mining, propose a data diagram for data-driven visualisation, tackle 2D-based drawing digitalisation, and support automated 3D conversion based on 2D drawing data.

DATA-DRIVEN VISUAL MODEL DEVELOPMENT

Data diagram design

A robust data diagram should ensure long-lasting support and compatibility with relevant data sources. In contrast to the standardised IFC framework prevalent in BIM, the mining industry currently needs a comparable standardised framework for 3D visual models. Furthermore, the focal points of visual model reconstruction differ significantly between sectors; for example, building engineering prioritises building parameters and materials, while mining engineering emphasises precise spatial location, geological information, and the structure of infrastructures (Huang *et al*, 2019; Wong *et al*, 2020; Li *et al*, 2021; Salmi and Heikkilä, 2023). Unlike the standardised building components referenced in the IFC parameters, mining operations often depend on original contour drawings, such as 2D CAD mine plans. This divergence necessitates a novel solution for underground mining, specifically tailored to its unique requirements, rather than adapting the standardised IFC framework.

This chapter specialises in visual model development in mining based on the proposed data diagram in Chapter 3. This diagram supports the integration of existing mine plan drawing data to increase the compatibility of visualisation development with existing data sources and align it with sustainable mine planning throughout a mine's operational life. The proposed design encompasses a comprehensive data diagram and its associated workflows, including data serialisation, cleaning, exchange, and information sharing.

Regarding data management research from recent studies, this paper selects NoSQL databases and the key-value format data. NoSQL databases provide a flexible and scalable approach to managing large volumes of unstructured data, which is often encountered in mining operations. The key-value format allows data to be stored in a way that enables efficient retrieval and processing, making it suitable for handling diverse and rapidly changing data sets (Membrey *et al*, 2010; Gudivada, Rao and Raghavan, 2014; Mohammadpoor and Torabi, 2018; Oussous *et al*, 2018; Qi, 2020; Liang *et al*, 2023). It enhances compatibility across diverse data sets to tackle ever-increasing data and variations in data fields. The data diagram includes six main fields presented in Figure 1: Grid ID, Grid coordination, Grid description, Timestamp, and Data Dictionary. The data dictionary contains detailed parameters that can serve for the reconstruction of a mining plan grid entity. The data dictionary can contain fields such as vertices collection, layer, timestamp, normal, extrude index, and future extension factors. The vertices collection is an array or list of 3D points of the model contour, where normal reflects the direction of the 3D extrude.

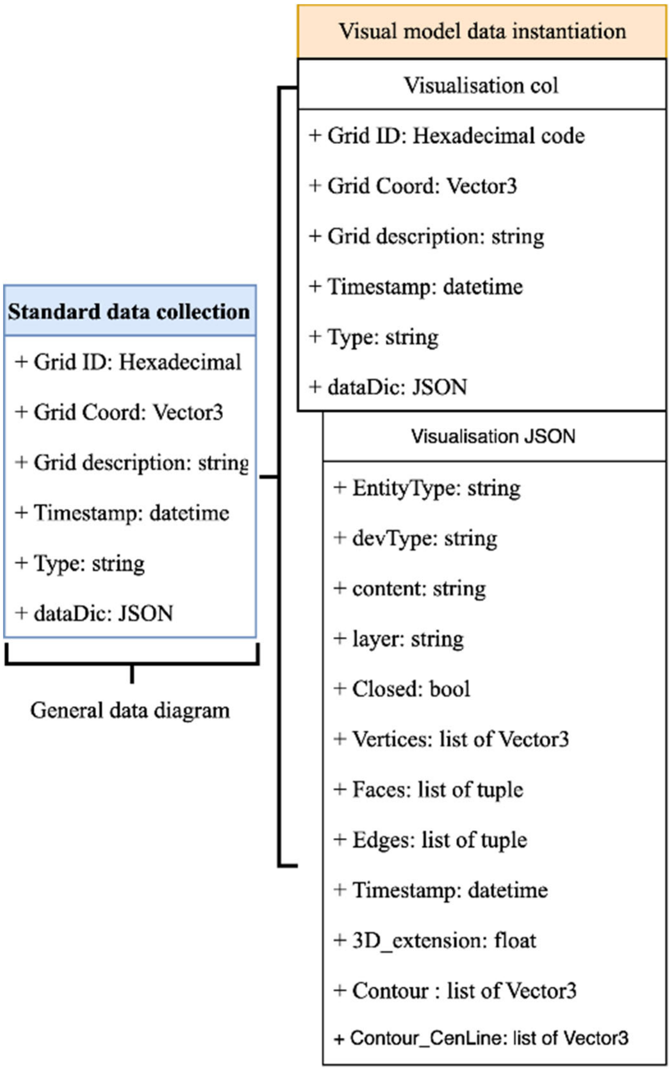


FIG 1 – Visual model data structure for mining visualisation.

Digitalisation of CAD files

This paper proposes a taxonomy to foster serialisation and visual model development and to standardise the visual model data, including section-based precise visual model, including tunnel, drop, shaft etc; polygon-based mine plan visual model, including tunnel, complex underground working areas, transport contiguous areas etc; representation-based dot visual model, including routine data, spatial distribution information etc; detailed 3D mesh visual model, including scanned point cloud model, faults, orebody, etc. The section-based visual model is extruded by a prefabricated section contour, following a specific centre line, as shown in Figure 2a. The polygon-based mine plan is the key type in this study, which is reconstructed as a 3D model with a 2D contour (Figure 2b). For routine data following spatial information and timestamps, the representation dot model is used in visualisation, as shown in Figure 2c. Finally, the visual mesh model can visualise complex 3D structures by digitalising the vertices and faces of a concave 3D structure (Figure 2d). Consequently, data-driven visualisation can develop the data diagram regarding the similarity across different properties in CAD files incorporating the taxonomy.

On the other hand, in mining drawings, CAD files normally contain three types of entities, including the closure contour entity, the annotation content, and the 3D structure. Closure contour entities such as POLYLINE, LWPOLYLINE, 3DPOLYLINE, 2DPOLYLINE, SPLINE, and 3DFACE will be converted to a closure POLYLINE, including vertices, closure status, and 3D extension value. For contour-based 3D creation, the data will include contour vertices and centre-line vertices. Annotation content, including TEXT and MTEXT, will be converted to TEXT with content and centre position. Regarding 3D structure, MESH/POLYFACE MESH will be converted to MESH with vertices, a face array consisting of 3-point index triangle faces, and an edge array consisting of 2-point index edges.

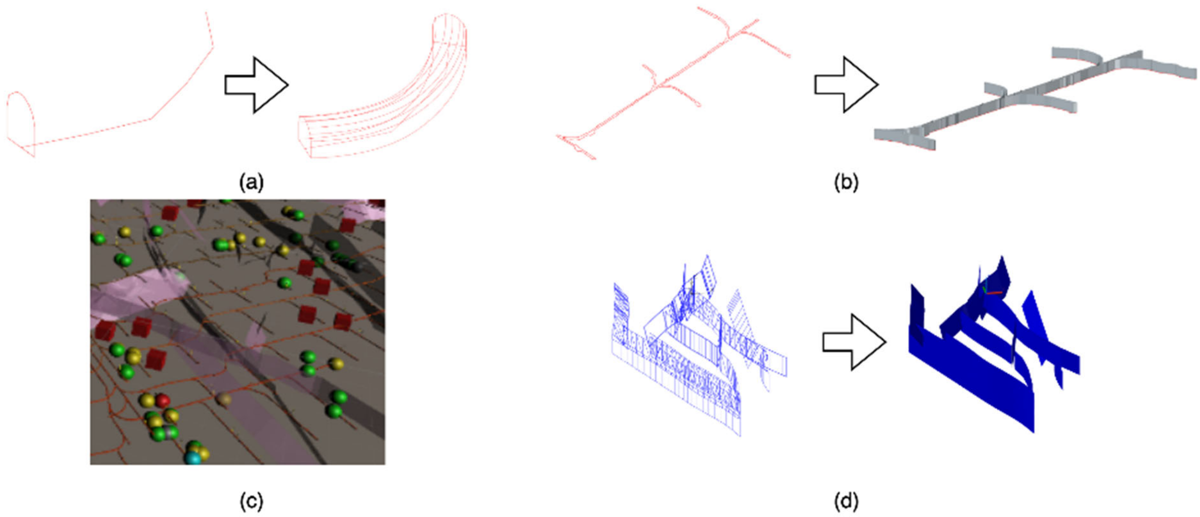


FIG 2 – Samples according to the visual model in underground mining: (a) Section-based precise visual model; (b) polygon-based mine plan visual model; (c) representation-based dot visual model; (d) Detailed 3D mesh visual model.

To unify and digitalise the drawing into generalised data for bidirectional interpolation, all entities will be converted to JSON data regarding the proposed data diagram in Figure 1. The bidirectional interpolation means the digitalised visual model data can also be interpreted into DXF drawings. The classification and corresponding data type for processing are listed below. With respect to the proposed conversion rules, the digitalisation process can address the challenges from drawings, such as the high density of vertices, odd planes, and self-interaction.

3D construction

Generic development components, such as tunnels and working areas, are reconstructed by convex polygons processed from data grid. For 2.5D visualisation and FPS roaming in this paper, mining workings have a basic mesh visualisation, which works for navigation, collider rendering, and interaction positioning. The 2.5D visualisation refers to a less detailed 3D visualisation with fixed perspective and transparent view for complex models. The mesh means that we demonstrate one single surface of a three-face polygon for transparent observation. In terms of 3D visualisation, the reconstruction of each grid entity will conduct 3D generation by extruding along with its normal direction. As a result, we also proposed a 3D construction taxonomy, including: development; complex concave and convex 3D contours; decline and shaft; section contour generation; panels; concave 3D contours; 3D structure; none-gridded, vertices, edges, and faces data sets.

Regarding the visualisation application, the generic visualisation scenarios include mining design overview, FPS roaming with precise visualisation, and 3D structure visualisation (revealing the correlations of geological and geotechnical connections). The mining design overview is presented as 2D wireframes, also called low-cost rendering mode, aiming to enhance performance in handling large-scale visualisation scenarios. It demonstrates the spatial connections of diverse data sets and visual models with a high FPS. The original polylines are visualised for the mine plan and production arrangement, which is shown in Figure 3a.

Dynamic rendering is proposed to optimise the visual model generation by virtual camera field of view. For example, in a roaming by first-person perspective in a tunnel, the visualisation can be limited to a range centred by the virtual camera, such as customised as 500 m visibility. The visual grid outside the visible range will be hidden and activated after encountering the valid range, which is shown in Figure 3b. For 3D geological and geotechnical, Figure 3d shows the spatial reliance of multifault zones across various data sets.

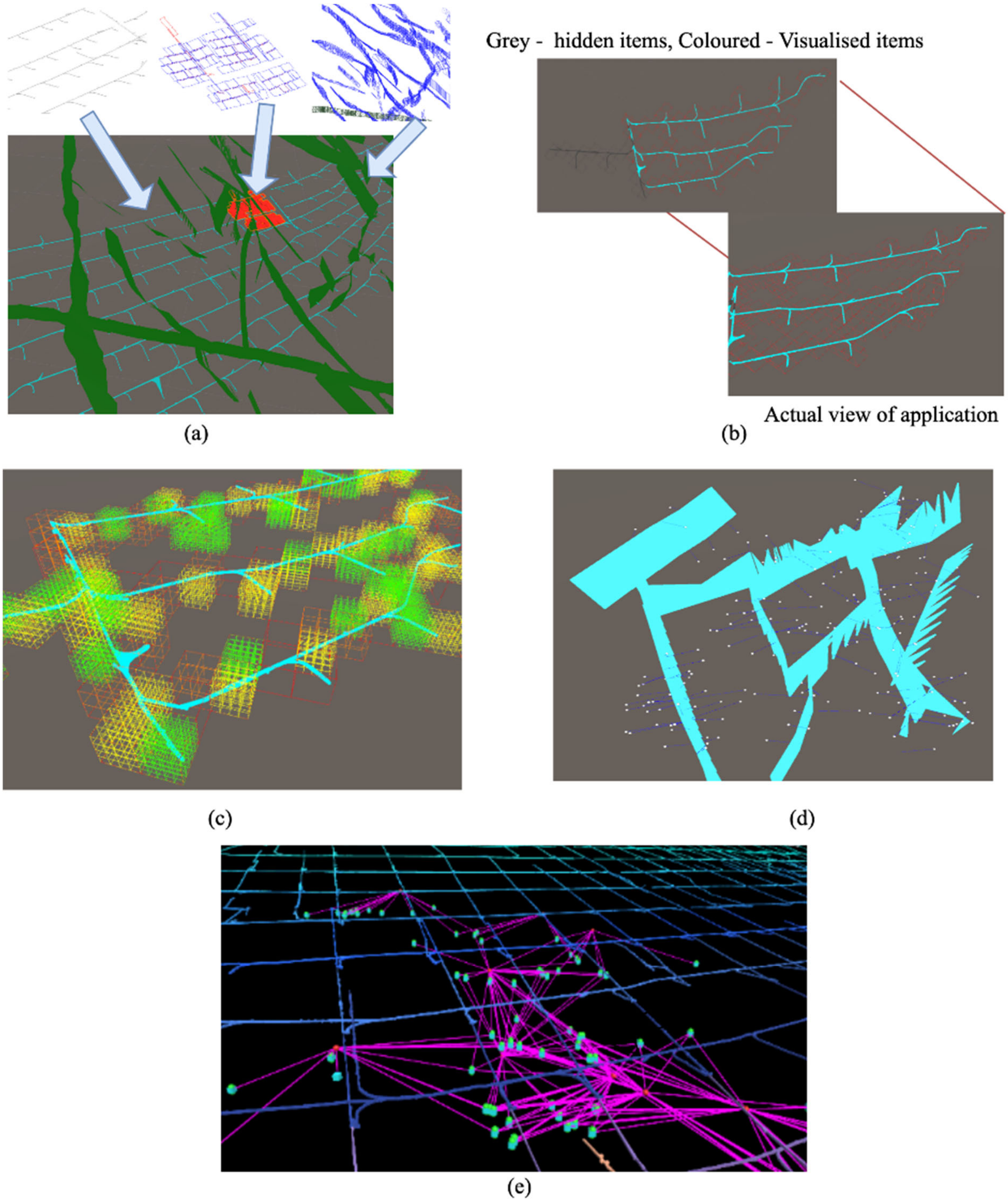


FIG 3 – Data-driven visualisation samples: (a) Overview of 2D to 3D generation; (b) Optimisation of the large-scale model renderer optimisation; (c) multimodality data gridding; (d) spatial distribution of geological structure and data; (e) Overview of spatial-temporal data visualisation.

Real-time generation and update

The DXF-based mining drawings, which follow the visual data processing standardisation, can be dragged in and visualised in real time. Correspondingly, users can be involved in validating and verifying the spatial distribution and confirming the update, which will be shown in a preview window after dropping in DXF files. The workflow is shown in Figure 4 illustrates the data validation process in the visual model update. Data overlapping and misposition data is identified through this flow.

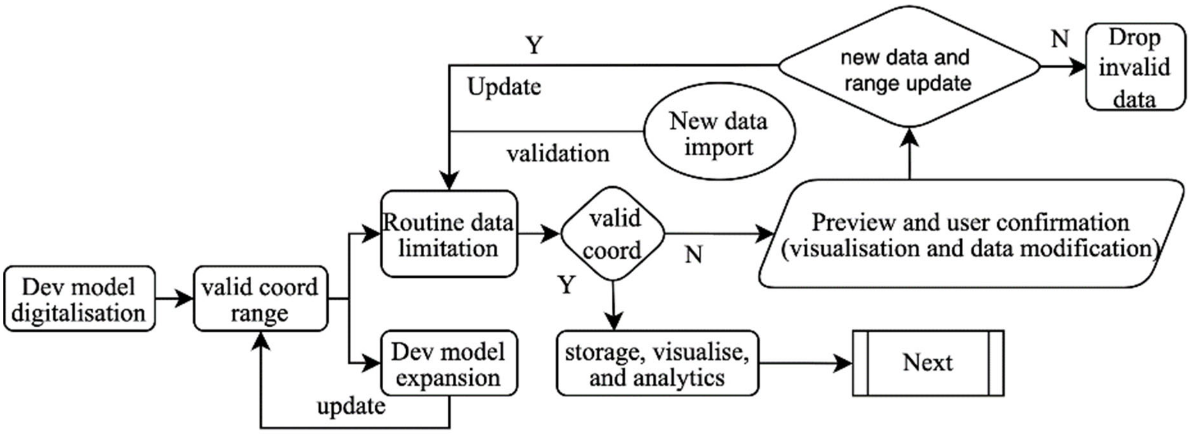


FIG 4 – System data validation workflow by the identified virtual model.

Specifically, new input drawings are processed into grids with spatial information using default settings. Then, spatial comparison is conducted to filter new grids and overlapping grids. For new grids, the data are directly uploaded to the service for visualisation and data management. For overlapping grids, data comparison is processed to identify the difference. Therefore, the preview window is demonstrated by one grid to get confirmation by user interaction.

In addition to DXF-based updates, users can also use a visual model extension interface for model updating. In this regard, the user can choose from section-based update, polygon-based update, or event-based update (spatial-temporal and data type information-based routine data update, as shown in Figure 5.

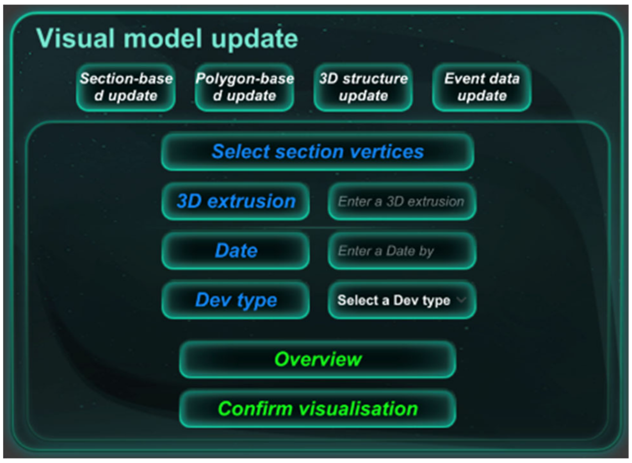


FIG 5 – UI sample for visual model update.

Visual model data management

With the support of the 3D tile index design, the visual model data management follows a strict hierarchy, as shown in Figure 6. The original cleaned visual mode data is stored in level 1 as basic resources. Then, gridding model data following user settings is level 2, which directly serves as visualisation data and 3D generation resources. Level 3 is the platform cache data, which includes visualised objects and updated data. The visual model data is modified and updated, then directly fed back to level 2, and finally re-integrated into the visual model data with feedback to level 1. Finally, cached data can be called via different function hierarchies, such as visualisation, interaction, and visual analytics.

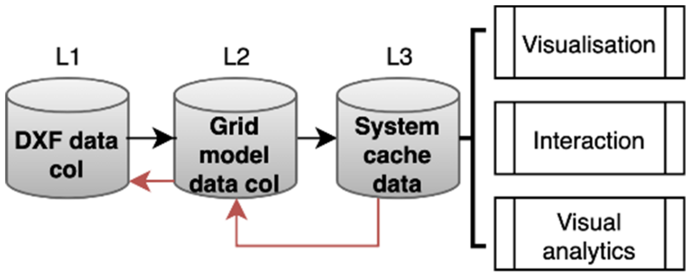


FIG 6 – Hierarchies for the management of visual model data.

For data-driven visual model management, the visual grid is the top-priority objective controlled by back-end programs. The management of visualised objectives in the proposed data-driven visual model development involves three hierarchies: **Grid**, taking over the visualisation status of all in-grid objects and data; **Layer**, the sub-level of each grid, receiving layer object control for visual analytics control. For example, multimodality data can be distinguished as different layers; the layer controller will take over the multi-layer visualisation in each grid; **Object**, the final receiver of user commands, takes over the object control, such as switching status, adjusting visualisation type, and feedback to interaction operation, through the message interpretation mechanism of the system.

DISCUSSION

Performance optimisation

The most important factor in evaluating a visualisation system is performance, especially in handling large-scale models and large amounts of multi-modality data. In this paper, the representations of the physical environment and various data are all 3D polygons. In terms of the increasing of vertices and faces from virtual objects, the Draw Calls and Batches in rendering will reach a super high and challenging stage, for example, one 3000 m (L) × 1000 m (W) × 1000 m (H) virtual mine model can generate the Draw Calls and Batches at more than 30 k, which puts the FPS to a relatively low level with around 10 (the moderate is 30). As a result, the optimisation of application performance is the most critical step for large-scale model visualisation and correlated interactions.

Object controller optimisation

Conventional visualisation depends on large-scale 3D solid models, and that is difficult to decide which part of the model should be visualised in specific scenarios. Actually, not all the models are visible while zooming in to a specific view. In this paper, benefiting from the 3D tile index solution, the 3D grid model optimises the minimum unit to control with. According to the virtual camera in a Unity3D scene, the distance between the target object and the virtual camera decides the priority in visualisation. The back-end calculation will be conducted with user interaction and interoperation to dynamically optimise the visualisation objects. As such, by incorporating a 3D tile index of the visual model and routine data, a design of a dynamic reflection mechanism to the visual grid will be a better solution to handle the increasing scale of a mine site visual model, in which the content of each 3D grid should automatically change the mode in 3D, 2.5D mesh, 2D contour, and even hidden status.

Physical simulation optimisation

In terms of the interaction design of the visualisation system, physical simulation aims to achieve customised user-virtual space interaction. For example, the collider component of an object decides the valid interaction zone. Due to the gridding of the 3D model, a large model has been decomposed into the standardised solid model, which reduces the concave complexity and makes the collider rendering more matched to its shape. However, increasing of complex colliders will challenge the performance due to the high cost of memory and calculation. As a result, the optimisation of physical simulation can be achieved with customised collider components. For instance, a tunnel with a detailed polygon collider, and a panel with a box collider, complex structure with a capsule or box collider, to reduce physical simulation calculation. In the next stage of this system, the adapted collider adjustment should be validated and verified for a real-time optimisation solution.

Drawing standardisation

Although this paper has proposed a visual analytics-orientated data diagram for data-driven model development, it is important to acknowledge that there can still be challenges in processing drawing data, particularly when it involves complex concave branches. In order to improve efficiency, it is essential to collect drawings under specific standardisation, especially considering that current mining drawings originate from nonunified procedures. Here are some suggestions for drawing data preparation:

- Close polygons: drawing entities should be identified and processed as independent components but not share any boundaries.
- Avoid complex concave polygons: concave polygons are challenging in gridding and 3D generation, which can also result in unforeseen self-interaction.
- Avoid self-intersection entities. 3D drawings in CAD systems are easy to have misposition errors due to the snap setting, which generally causes self-interaction and unforeseen evaluation variation.

CONCLUSIONS

This paper proposes a data-driven visual model development solution, which is based on widely utilised CAD files. A visual model data diagram and correlated workflows are proposed for high-fidelity and real-time visual model reconstruction. In summary, the data-driven visual model development provides an automated and real-time visualisation solution for lifetime maintenance and sustainable development. It enhances human recognition and judgement in data analytics by incorporating visual analytics design. Furthermore, the visual model involved in data visualisation and analysis plays an important role in the development of data fusion. Based on the data-driven visual platform, more multimodal data visualisation and analytics can be achieved in the future, including the construction of a mining digital twin system.

REFERENCE

Barnewold, L and Lottermoser, B G, 2020. Identification of digital technologies and digitalisation trends in the mining industry, *International Journal of Mining Science and Technology*, 30(6):747–757.

Beckett, S, 2022. Smart city digital twins, 3D modeling and visualization tools and spatial cognition algorithms in artificial intelligence-based urban design and planning, *Geopolitics, History and International Relations*, 14(1):123–138.

Boje, C, Guerriero, A, Kubicki, S and Rezgui, Y, 2020. Towards a semantic Construction Digital Twin: Directions for future research, *Automation in Construction*, 114:103179.

Boschert, S and Rosen, R, 2016. Digital Twin—The Simulation Aspect, *Mechatronic Futures: Challenges and Solutions for Mechatronic Systems and their Designers*, pp 59–74 (Cham, Springer International Publishing).

Cameron, D B, Waaler, A and Komulainen, T M, 2018. Oil and Gas digital twins after twenty years, How can they be made sustainable, maintainable and useful?, in *Proceedings of The 59th Conference on Simulation and Modelling (SIMS 59)*, pp 9–16.

Cui, W, 2019. Visual Analytics: A Comprehensive Overview, *IEEE Access*, 7:81555–81573.

Duarte, J, Fernanda Rodrigues, M and Baptista, J, 2020. *Data Digitalisation in the Open-Pit Mining: Preliminary Results*, pp 715–723 (Springer International Publishing).

Elbazi, N, Mabrouki, M, Chebak, A and Hammouch, F, 2022. Digital Twin Architecture for Mining Industry: Case Study of a Stacker Machine in an Experimental Open-Pit Mine, 4th Global Power, Energy and Communication Conference, IEEE GPECOM2022.

Gudivada, V N, Rao, D and Raghavan, V V, 2014. NoSQL Systems for Big Data Management, 2014 IEEE World Congress on Services.

Huang, S, Wang, H, Yu, J, Feng, X, Wang, X, Tang, Y and Lang, H, 2019. Construction of Intelligent Mine Information System Based on BIM and GIS, *Value Engineer*, 38(11):184–186.

Li, W, Li, S, Lin, Z and Li, Q, 2021. Information modeling of mine working based on BIM technology, *Tunnelling and Underground Space Technology,* 115:103978.

Liang, R, Huang, C, Zhang, C, Li, B, Saydam, S and Canbulat, I, 2023. Exploring the Fusion Potentials of Data Visualization and Data Analytics in the Process of Mining Digitalization, *IEEE Access*, 11:40608–40628.

Liang, R, Xu, S, Hou, P and Zhu, C, 2019. Research on 3D Modeling Technology of Mining Method for Underground Mining of Metallic Deposits, *China Mining Magazine*, 28(03):73–77.

Liang, R, Xu, S, Shen, Q and An, L, 2018. Research and Development of Dynamic Simulation System for Mining Method Based on Unity3D, *Metal Mine*, (02):141–145.

Ltifi, H, Kolski, C and Ayed, M B, 2020. Survey on Visualization and Visual Analytics pipeline-based models: Conceptual aspects, comparative studies and challenges, *Computer Science Review*, 36:100245.

Lu, Q, Chen, L, Li, S and Pitt, M, 2020. Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings, *Automation in Construction*, 115:103183.

Membrey, P, Plugge, E, Hawkins, T and Hawkins, T, 2010. *The definitive guide to MongoDB: the noSQL database for cloud and desktop computing* (Springer).

Mohammadpoor, M and Torabi, F, 2018. Big Data analytics in oil and gas industry: An emerging trend, *Petroleum*.

Oussous, A, Benjelloun, F-Z, Ait Lahcen, L and Belfkih, S, 2018. Big Data technologies: A survey, *Journal of King Saud University - Computer and Information Sciences*, 30(4):431–448.

Qi, C, 2020. Big data management in the mining industry, *International Journal of Minerals, Metallurgy and Materials,* 2(27):131–139.

Sacha, D, Kraus, M, Keim, D A and Chen, M, 2019. VIS4ML: An Ontology for Visual Analytics Assisted Machine Learning, *IEEE Transactions on Visualization and Computer Graphics*, 25(1):385–395.

Salmi, J and Heikkilä, R, 2023. Information Modelling Guidelines for the Mining Sector, in Proceedings of the International Symposium on Automation and Robotics in Construction – ISARC (IAARC Publications).

Sishi, M and Telukdarie, A, 2020. Implementation of Industry 4.0 technologies in the mining industry - a case study, *International Journal of Mining and Mineral Engineering,* 11(1):1–22.

Sun, Z, Lu, X and Tian, M, 2009. Research and Implementation of 3D Modeling Algorithm for Mine Roadway, *Acta Geodaetica et Cartographica Sinica*, 38(03):250–254.

Wong, J-Y, Yip, C-C, Yong, S-T, Chan, A, Kok, S-T, Lau, T-L, Ali, M T and Gouda, E, 2020. BIM-VR Framework for Building Information Modelling in Engineering Education, *International Journal of Interactive Mobile Technologies,* 14(6).

Xie, X and Lu, X, 2017. Development of a 3D modeling algorithm for tunnel deformation monitoring based on terrestrial laser scanning, *Underground Space*, 2(1):16–29.

Zhu, Q, Liu, J, Gao, L, Chen, Z and Liu, X, 2018. Modeling and Inversion of Complex 3D Geologic Field Stress and Its Application in Rockburst Evaluation, in *Proceedings of GeoShanghai, 2018 International Conference: Rock Mechanics and Rock Engineering*, pp 352–363 (Springer Singapore).

Predictive spatial modelling of rock mass properties using machine learning techniques

Y Liu[1], M Karakus[2] and J Q Shi[3]

1. Research Fellow, Australian Institute for Machine Learning, The University of Adelaide, Adelaide SA 5000. Email: yuhang.liu01@adelaide.edu.au
2. Associate Professor, Mining and Petroleum Engineering, The University of Adelaide, Adelaide SA 5000. Email: murat.karakus@adelaide.edu.au
3. Professor, Australian Institute for Machine Learning, The University of Adelaide, Adelaide SA 5000. Email: javen.shi@adelaide.edu.au

ABSTRACT

Predicting the spatial distribution of rock mass properties in cave mining is a critical challenge. In this study, we introduce a novel machine learning-based model to advance our comprehension of rock behaviour. This model specifically focuses on the spatial distribution of rock mass and mechanical properties, a crucial aspect of our understanding of rock mechanics. Our model is inspired by the recognition that neighbouring information serves as crucial prior knowledge for predicting the spatial distribution of these properties, wherein closer neighbours are likely to exhibit similar characteristics. To effectively capture and model these neighbour relationships, we design a neural network-based model to map the spatial locations within the data set into a new high-dimensional space. Within this transformed space, we utilise Euclidean distance to identify N neighbours. Leveraging these neighbours, we introduce a straightforward yet highly effective approach—label propagation—to construct a graph that illustrates neighbour relationships. This graph not only facilitates the prediction of the spatial distribution of rock mass properties but also offers a measure of uncertainty for these predictions. We validate the proposed method using a real rock data set and showcase its efficacy in capturing intricate relationships and distributions within rock properties, enabling precise predictions across diverse spatial scales. Our results underscore the potential of machine learning-based approaches to revolutionise the field of rock mechanics, providing valuable insights applicable to geotechnical engineering, mining, and other sectors where an accurate understanding of rock properties is paramount. This model has direct practical implications, offering a new tool for geotechnical engineers and mining professionals to enhance their understanding and prediction of rock properties, thereby improving safety and efficiency in their operations.

INTRODUCTION

Geotechnical design deals with many uncertainties about how the ground behaves under various loading conditions and requires a large amount of data for a robust design of underground structures. To gather the right data, engineers use a range of methods like field measurements, laboratory tests, drilling, and surveys (Jaeger, Cook and Zimmerman, 2009; Mogi, 2006). The aim is to understand rock mechanical and rock mass properties, like how they deform and their stiffness, eg uniaxial compressive strength, spacing of discontinuities and Groundwater conditions, which helps in designing structures safely (Fereidooni, 2016; Karakus, Kumral and Kilic, 2005). One traditional method to obtain rock mass and mechanical properties is through direct measurement techniques, involving experimental methods applied either to the rock mass in the field or to rock material in the laboratory (Azarafza *et al*, 2019; Barham *et al*, 2020). These experiments usually entail specific instructions, equipment, and procedures determined at various stages (Feng, 2017). One main advantage of using measurement techniques is their ability to provide accurate estimations for rock mass and mechanical properties. However, while accurately estimating geomechanical properties is crucial for successful design and construction assurance, direct procedures in the field are often expensive and time-consuming. Instead of relying solely on the aforementioned direct measurement techniques, another alternative involves leveraging machine learning methods. These approaches can provide valuable insights while reducing both cost and time, making them an appealing option. Various machine learning procedures, such as neural networks (Torabi-Kaveh *et al*, 2015), fuzzy logic (Karakus and Tutmez, 2006), and multilayer perceptron models (Gultekin, Gokceoglu and

Sezer, 2013), have been employed to develop predictive models and ascertain the necessary geomechanical indices and rock mass parameters. Among these methods, neural networks (Sun *et al*, 2020) have particularly demonstrated significant success in generating predictive models for estimating the geomechanical properties of rock masses. This is partly due to the complex modelling capabilities of neural networks and recent advances in their implementation. One primary motivation behind this work is that traditional neural network-based methods may not effectively utilise a key piece of prior knowledge in the analysis of rock mass properties: neighbour information. This prior knowledge is often inherent in rock mass properties, as neighbouring rocks are likely to exhibit similar characteristics. To effectively capture and model these neighbour relationships, this work proposes combining neural networks and neighbour information to predict a spatial model of rock mass properties. Specifically, we first design a neural network-based model to map the spatial locations within the data set into a new high-dimensional space. Within this transformed space, we utilise Euclidean distance to identify N neighbours. Leveraging these neighbours, we introduce a straightforward yet highly effective approach—label propagation—to construct a graph that effectively incorporates neighbour information for prediction. As a result, the proposed method seamlessly integrates neural networks and neighbour information into a framework. The primary advantage of neural networks in modelling complex nonlinear mappings is that they are utilised to map the original spatial locations to a new space. Within this space, Euclidean distance is employed to define neighbours. Moreover, based on the defined neighbours, we can employ label propagation to effectively predict the spatial distribution of rock mass properties. We conduct experiments on real data sets and verify the effectiveness of the proposed method.

DATA AND PREPROCESSING

The data set we used comprises five essential rock mass rating parameters: uniaxial compressive strength of rock material, rock quality designation, spacing of discontinuities, condition of discontinuities, and groundwater conditions. Within the condition of discontinuities parameter, we delve into five sub-parameters: discontinuity length, aperture, roughness, infill, and weathering. These parameters undergo an initial assessment by geotechnical experts, and their ratings serve as the foundation for subsequent experimental investigations. The rating is an outcome of a classification of each parameter. The range of ratings for each parameter is presented in Table 1. Each value of each parameter has been associated with a 3D location index, eg x, y and z, indicating the source of its value.

TABLE 1

The range of ratings for each parameter of rock mass properties.

Rock Mass Rating Parameters	Ratings
Uniaxial compressive strength of rock material	0 to 15
Rock quality designation	3 to 20
Spacing of discontinuities	5 to 20
Condition of discontinuities: length	0 to 6
Condition of discontinuities: aperture	0 to 6
Condition of discontinuities: roughness	0 to 6
Condition of discontinuities: infill	0 to 6
Condition of discontinuities: weathering	0 to 6
Groundwater conditions	0 to 15

The expansive geographical coverage of our collected data naturally includes outliers situated far from the central cluster, as vividly portrayed on the left side of Figure 1. These outliers consistently pose formidable challenges during machine learning model training. In response, we adopt rigorous data filtering techniques to selectively preserve closely clustered data points, effectively mitigating the uncertainties they introduce. The resulting refined data distribution, showcased on the right side of Figure 1, underscores the efficacy of our approach.

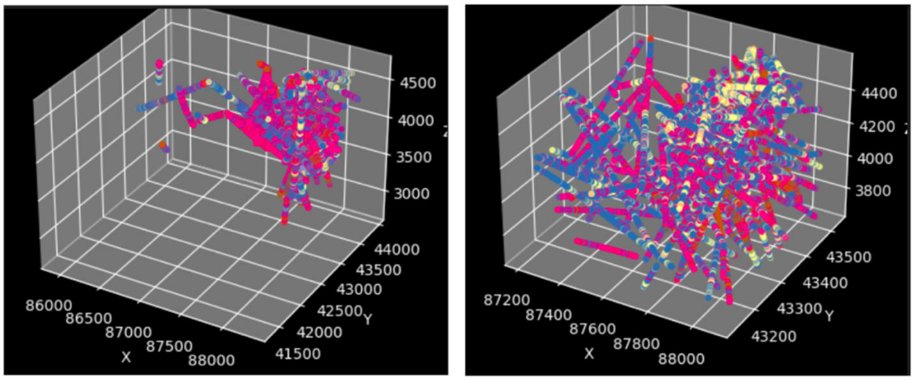


FIG 1 – The visual representation depicts the spatial distribution of the collected data. On the left, we observe the distribution of the original data, whereas the right showcases the refined data distribution.

METHOD

Our model draws inspiration from the recognition that neighbouring information plays a pivotal role in predicting the spatial distribution of rock mass properties. It is commonly observed that closer neighbours tend to share similar characteristics. This observation motivates us to employ a straightforward yet powerful technique, label propagation (Zhou *et al*, 2023), for predicting rock mass properties.

However, traditional label propagation methods assume that all neighbours share the same label, which can be restrictive. However, in reality, certain neighbours may exhibit inconsistent characteristics compared to the broader neighbourhood. To overcome this limitation, we propose a more adaptable assumption: the existence of a latent space where neighbours possess consistent labels. Motivated by this insight, we develop a neural network-based model to map spatial locations within the data set into a new high-dimensional space. Within this transformed space, we utilise Euclidean distance to identify N neighbours. Leveraging these neighbours, we introduce a straightforward yet highly effective approach—label propagation—to construct a graph illustrating neighbour relationships. This graph not only facilitates the prediction of the spatial distribution of rock mass properties but also provides a measure of uncertainty for these predictions. The proposed model is depicted in Figure 2. The proposed model is trained using the label propagation loss function, such as cross-entropy, which compares the true ratings of parameters listed in Table 1 in the training data with the ratings predicted by label propagation. Consequently, the neural network adapts the new latent space dynamically based on the loss function.

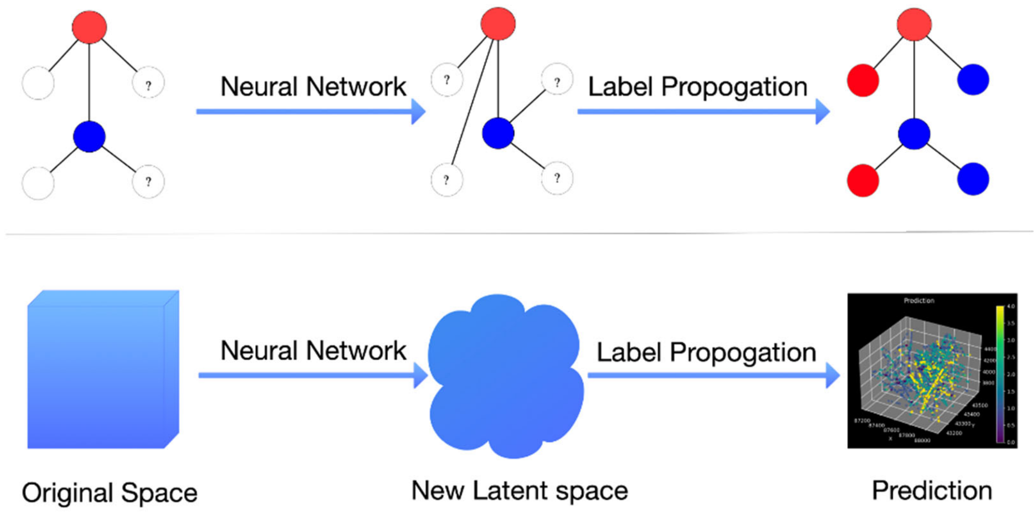


FIG 2 – The proposed model utilises a neural network-based approach to map spatial locations within the data set onto a newly defined high-dimensional space, followed by employing label propagation for final prediction. The upper section illustrates an example of spatial location mapping to the new latent space and the prediction process using label propagation, while the bottom part presents the framework.

RESULTS

As underlined in the Data Preprocessing section, we partitioned the entire data set into three subsets: training data (80 per cent), validation data (10 per cent), and test data (10 per cent). After optimising the proposed model with the training data and selecting a model using the validation data, the test data results are shown in Table 2.

TABLE 2

The results on rock mass properties, eg condition of discontinuities, by different methods.

Methods	Networks	Train	Validation	Test
Multilayer Perceptron	Linear(Relu(Linear))	38.52%	38.52%	38.52%
K-Nearest Neighbours (k=3)		78.06%	59.73%	60.28%
K-Nearest Neighbours (k=5)		80.36%	72.32%	73.36%
Label Propagation		98.17%	97.72%	74.88%

Table 2 illustrates that the proposed model surpasses neural network-based methods, K-Nearest Neighbours methods, and traditional label propagation. In comparison, K-Nearest Neighbours methods and label propagation exhibit notable advantages in terms of testing accuracy, which validates our core insight that neighbouring rock masses are likely to share similar characteristics. Furthermore, our proposed method employs a neural network to derive a new latent space in which label propagation performs even better than in the original spatial location space. These findings underscore the presence of a latent space where neighbouring entities consistently exhibit shared labels, aligning with our assertion that certain neighbours may demonstrate inconsistent characteristics compared to the broader neighbourhood.

With the support of results in experimental Protocol 1, we now turn to predict the whole spatial distribution of rock mass properties. Again, after optimising the proposed model with the training data and selecting a model using the validation data, the predictions of the whole spatial distribution for various rock mass properties are depicted by Figures 3, 4 and 5.

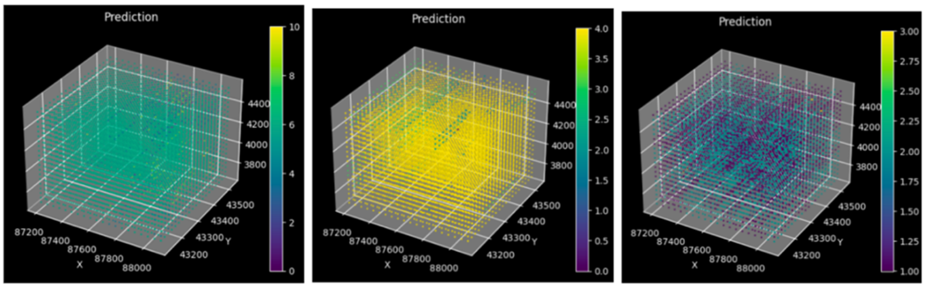


FIG 3 – Predictions of the spatial distributions for uniaxial compressive strength of rock material (left), rock quality designation (middle), spacing of discontinuities (right), and different colours representing different ratings.

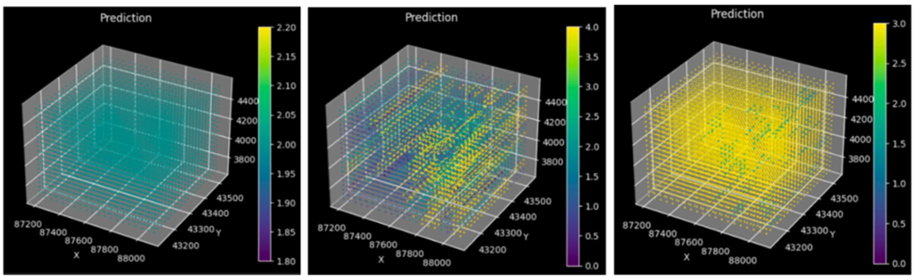


FIG 4 – Predictions of the spatial distributions for the condition of discontinuities: length (left), condition of discontinuities: aperture (middle), and condition of discontinuities: roughness (right), with different colours representing distinct ratings.

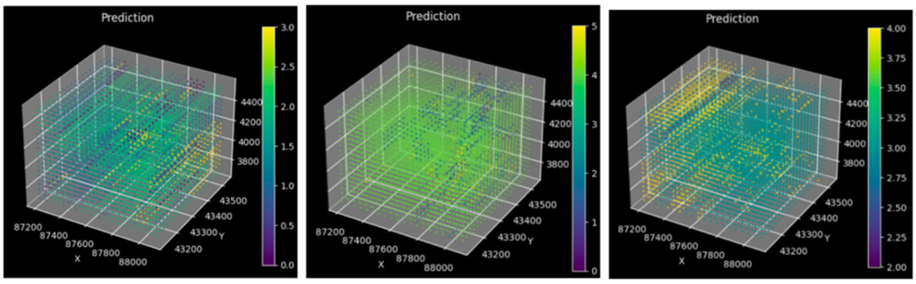


FIG 5 – Predictions of the spatial distributions for the condition of discontinuities: infill (left), condition of discontinuities: weathering(middle), and groundwater conditions (right), with different colours representing distinct ratings.

CONCLUSION

In this study, we introduce significant prior knowledge for predicting rock mass properties using machine learning methods. This insight highlights the importance of neighbouring information, where nearby data points are likely to share similar characteristics, influencing the spatial distribution of these properties. Guided by this understanding, we present a novel approach that combines neural networks and label propagation to predict the spatial distribution of rock mass properties. This method has been validated using real data and demonstrates promising performance. The exploration of neighbouring information proves to be both significant and intriguing for the prediction of rock mass properties.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support from the Australian Research Council and industry partner BHP for funding this research under project ARC-LP200100038.

REFERENCES

Azarafza, M, Ghazifard, A, Akgun, H and Asghari-Kaljahi, E, 2019. Geotechnical characteristics and empirical geo-engineering relations of the south pars zone marls, Iran, *Geomechanics and Engineering,* 19:393.

Barham, W S, Rabab'ah, S R, Aldeeky, H H and Hattamleh, O H Al, 2020. Mechanical and physical based artificial neural network models for the prediction of the unconfined compressive strength of rock, *Geotechnical and Geological Engineering,* 38:4779.

Fereidooni, D, 2016. Determination of the geotechnical characteristics of hornfelsic rocks with a particular emphasis on the correlation between physical and mechanical properties, *Rock Mechanics and Rock Engineering*, 49:2595–2608.

Feng, X-T, 2017. *Rock mechanics and engineering volume 2: Laboratory and field testing* (CRC Press).

Gultekin, N U, Gokceoglu, C and Sezer, E A, 2013. Prediction of uniaxial compressive strength of granitic rocks by various nonlinear tools and comparison of their performances, *International Journal of Rock Mechanics and Mining Sciences*, 62:113–122.

Jaeger, J C, Cook, N G and Zimmerman, R, 2009. *Fundamentals of rock mechanics* (John Wiley & Sons).

Kaveh, M T, Naseri, F, Saneie, S and Sarshari, B, 2015. Application of artificial neural networks and multivariate statistics to predict UCS and e using physical properties of a smart limestones, *Arabian Journal of Geosciences*, 8:2889–2897.

Karakus, M, Kumral, M and Kilic, O, 2005. Predicting elastic properties of intact rocks from index tests using multiple regression modelling, *International Journal of Rock Mechanics and Mining Sciences*, 42(2):323–330.

Karakus, M and Tutmez, B, 2006. Fuzzy and multiple regression modelling for evaluation of intact rock strength based on point load, Schmidt hammer and sonic velocity, *Rock mechanics and rock engineering*, 39:45–57.

Mogi, K, 2006. *Experimental rock mechanics* (CRC Press).

Sun, D, Lonbani, M, Askarian, B, Armaghani, D J, Tarinejad, R, Pham, B T and Huynh, V V, 2020. Investigating the applications of machine learning techniques to predict the rock brittleness index, *Applied Sciences*, 10:1691.

Zhou, D, Bousquet, O, Lal, T, Weston, J and Sch ̈olkopf, B, 2003. Learning with local and global consistency, *Advances in neural information processing systems*, 16.

Artificial Intelligence (AI)-based predicting influence of technological innovation on stock price of iron ore mining companies

P Mugebe[1], M S Kizil[2], M Yahyaei[3] and R Low[4,5]

1. MAusIMM(CP), PhD student, The University of Queensland, School of Mechanical and Mining, St Lucia Qld 4067. Email: p.mugebe@uq.edu.au
2. MAusIMM, Associate Professor, The University of Queensland, School of Mechanical and Mining, St Lucia Qld 4067. Email: m.kizil@uq.edu.au
3. Professor, The University of Queensland, Julius Kruttschnitt Mineral Research Centre, Indooroopilly Qld 4067. Email: m.yahyaei@uq.edu.au
4. Honorary Senior Fellow, The University of Queensland, School of Business, St Lucia Qld 4067. Email: r.low@business.uq.edu.au
5. Associate Professor, Bond University, Bond Business School, Robina Qld 4225. Email: rlow@bond.edu.au

INTRODUCTION

This paper seeks to establish an empirical relationship between the impact of mining technological innovation implementation and a company's market value. The company's market value is represented by its stock price. In a bid to ascertain the relationship, a stock price prediction model is sought to be established using the firm-specific factors impacted by the implementation of innovative technology. This work is performed under the watch of the prevailing macroeconomic factors. The background anchors in the understanding that the difference between the economic status of a mineral deposit and its uneconomic status lies in the level of mining technological innovation most prevalent at a given time (Hartwick, Olewiler and Preuss, 1986; Wellmer and Scholz, 2017; Wright and Czelusta, 2003). This is derived from productivity improvement, resulting in sustainable profitability due to technological innovation. Unfortunately, there is not an adequately established relationship that links this technological innovation impact to the share price performance of the mineral commodity company.

Artificial Intelligence (AI) is currently used in building share price prediction models using technical information as the input data. Presently, there is not such models based on firm-specific and macroeconomic fundamental information as the input data. This shortfall creates scope to explore the use of AI to develop an empirical relationship between mining technological innovation implementation and share price in the form of a prediction model. The prediction model of which can be used by public investors in decision-making when investing in mineral commodity stocks, and by mining companies as an additional internal new technology investment approval tool.

The upside of AI is that the results are often reliable since it uses Artificial Neural Network (ANN) prediction which can merge data of diverse formats and structures. The data analysis can accommodate less precise or incomplete input data due to the distributed characteristic of information processing (Sureshkumar and Elango, 2012). This makes it possible to produce accurate share price predictions even with uncertain data as it can integrate with other methods that can compensate for the data deficiency. However, while it is used to accurately forecast stock prices and stock market index prices, the input data has been historical technical indicators such as stock's day open price, closing price, low and high prices, and price moving average (Di Persio and Honchar, 2016; Prasanna and Ezhilmaran, 2013; Shah, Isah and Zulkernine, 2019). The array of input data sets excludes fundamental factors that influence the stock price performance. So, is AI equally applicable in stock price prediction based on fundamental factors as it is on technical indicators? If so, are similar levels of accuracy achievable? In this study, the fundamental factors considered are the share price driving variables influenced, either directly or indirectly, by the implementation of an autonomous haulage system (AHS) in an open pit iron ore mine under prevailing macroeconomic factors.

The importance of this study is to give an indication of whether the results obtained, based on fundamental factors, are functionally reliable or not. It also investigates the weight of the respective factors in driving the share price performance. Once these two tasks are satisfactorily addressed, then the methodology can be accepted as a tool for evaluating the impact of technological innovation on share price performance. The objectives of the study are, thus: i) to figure out the AI tools that can be used in building the share price prediction models, ii) develop a share price prediction model based on firm-specific and macroeconomic fundamental factors, and iii) rank the factors according to their weights in driving the share price performance.

Literature survey (Pawar, Jalem and Tiwari, 2019; Yu *et al*, 2019; Jhang *et al*, 2019) established that many ANN architectures are used to build share price prediction models. The models vary in their structures and levels of accuracy and reliability. The most common ones are:

- Convolutional Neural Network (CNN)
- Recurrent Neural Network (RNN)
- Long Short-Term Memory (LSTM)
- Convolutional Recurrent Neural Network (ConvLSTM)
- Convolutional Recurrent Neural Network with Attention (ConvLSTM with Attention).

The LSTM architecture was preferred as it has a simple but robust structure which can be easily adjusted to improve accuracy. Pawar, Jalem and Tiwari (2019), Yu *et al* (2019), and Jeevan *et al* (2018) demonstrate that LSTM is the main backbone of ANN structures used for stock price prediction models. It is the most suited architecture for machine learning predictions that are time-series based compared to others which such as RNN which are more suited to pictorial detection and prediction.

In a bid to obtain suitable input firm-specific data for the study, Fortescue Metals Group (FMG) share price performance was investigated during and after the AHS implementation period in their iron ore operation. The productivity improvement metrics and the resultant financial performance indicators affected by the technological implementation were tracked from the technology inception in 2012 to its completion in 2020 (FMG, 2020; Gölbaşı and Dagdelen, 2017; Leonida, 2019). The macroeconomic factors, judged to closely affect iron ore share price, which are AUD/USD exchange rate and the iron ore price, were tracked over the same period. The data was processed to make it compatible with LSTM, the selected AI methodology. Python programming language was used to build the LSTM share price prediction model. Table 1 shows the input and output variables for the LSTM model.

TABLE 1

LSTM Model input data parameters.

Input			**Output**	
Parameter	**Frequency**		**Parameter**	**Frequency**
Mining and processing cost per tonne	Quarterly	Firm-specific	Share price	Daily
Stripping ratio	Quarterly	Firm-specific		
Net profit margin	Quarterly	Firm-specific		
Net gearing ratio	Yearly	Firm-specific		
Current ratio	Yearly	Firm-specific		
Net interest cover	Yearly	Firm-specific		
Return on equity (ROE)	Yearly	Firm-specific		
Return on assets (ROA)	Yearly	Firm-specific		
Cumulative daily average sentiment	Daily	Firm-specific		
Volume of stock trades	Daily	Firm-specific		
Technology size	Daily	Firm-specific		
Exchange rate	Daily	Macroeconomic		
Iron ore price	Monthly	Macroeconomic		

The model results were satisfactory, especially after adjusting for the black swan events (BSE) that took place during the period under review. The BSE were the Brumadinho tailings dam collapse in Brazil in January 2019, resulting in the suspension of 5.6 per cent of the world's iron ore supply (Ker, 2024) and the Covid-19 pandemic starting in December 2019. Figure 1 shows the output of the LSTM model.

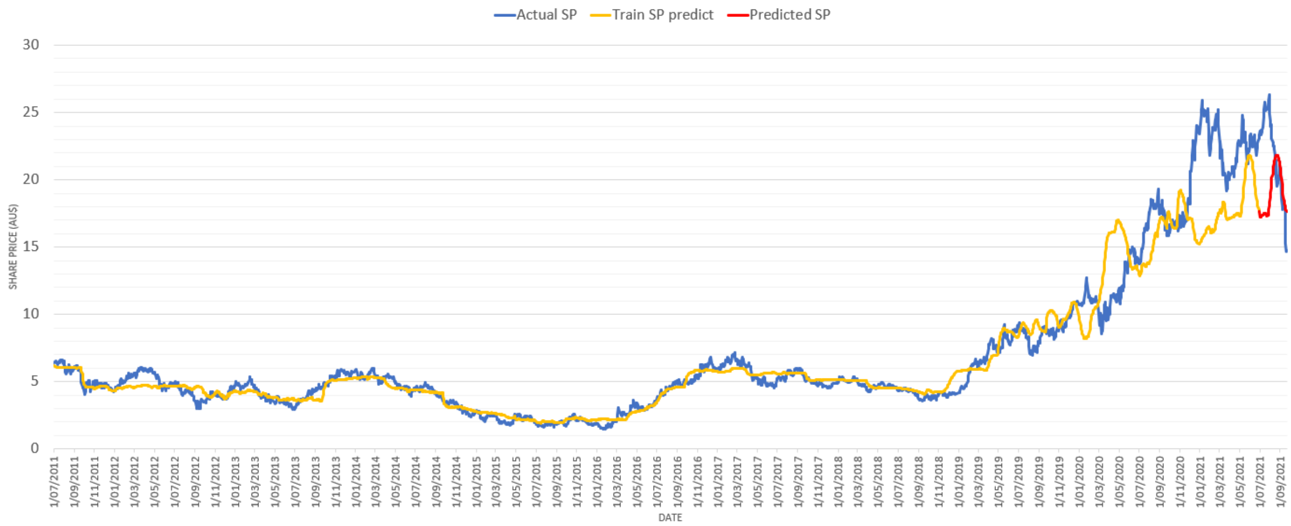


FIG 1 – LSTM model – FMG share price performance. Notes: *Actual SP* – The actual share price performance. *Train SP predict* – The predicted share price during the training phase of the model. *Predicted SP* – The predicted share price for the period beyond the training phase.

To understand the factors that are most predominant in driving the share price performance, the Principal Component Analysis (PCA) technique, coded in Python programming language, is used. The factors are then ranked in order of their weight in influencing the share price performance.

The results reveal that if fundamental factors are used as input data to an AI share price prediction model, satisfactory results can be achieved. However, the level of accuracy was less for short-term due to the low frequency of the input data, but better for long-term prediction. The PCA technique confirms that mining related factors impacted, directly or indirectly, by technology implementation rank highly in influencing the share price performance. Therefore, the study added a milestone in the journey of establishing an empirical relationship between the impact of mining technological innovation implementation and a company's market value.

ACKNOWLEDGEMENTS

Sincere gratitude goes to the research advisors, Associate Professors Mehmet Kizil, Mohsen Yahyaei, and Rand Low, for their support and encouragement. The University of Queensland is equally acknowledged for providing the necessary resources for the research.

REFERENCES

Di Persio, L and Honchar, O, 2016. Artificial neural networks architectures for stock price prediction: Comparisons and applications, *International Journal of Circuits*, *Systems and Signal Processing*, 10(2016):403–413.

FMG, 2020. Fortescue automation deployment reaches significant milestone, FMG. Available from: <https://www.fmgl.com.au/in-the-news/media-releases/2020/06/23/fortescue-automationdeployment-reaches-significant-milestone> [Accessed: 02/09/2020].

Gölbaşı, O and Dagdelen, K, 2017. Equipment replacement analysis of manual trucks with autonomous truck technology in open pit mines, presented at Proceedings of the 38th International Symposium on the Application of Computers and Operations Research (APCOM) 2017.

Hartwick, J M, Olewiler, N D and Preuss, R, 1986. *The economics of natural resource use* (Harper and Row Publishers: New York).

Jeevan, B, Naresh, E, Kumar, B P V and Kambli, P, 2018. Share Price Prediction using Machine Learning Technique, in *Proceedings IEEE Third International Conference on Circuits, Control, Communication and Computing*, pp 1–4.

Jhang, W S, Gao, S E, Wang, C M and Hsieh, M C, 2019. Share Price Trend Prediction Using Attention with LSTM Structure, in *Proceedings IEEE World Congress on Services*, pp 208–211.

Ker, P, 2024. The most unfortunate fortune Australia will ever make, *Financial Review*. Available from: <https://www.afr.com/companies/mining/the-most-unfortunate-fortune-australia-will-ever-make-20240111-p5ewli> [Accessed: 13/02/2024].

Leonida, C, 2019. Optimizing Autonomous Haulage, Equipment replacement analysis of manual trucks with autonomous truck technology in open pit mines, in *Proceedings of the 38th International Symposium, Engineering and Mining Journal,* 220(12):36–43.

Pawar, K, Jalem, R S and Tiwari, V, 2019. Stock Market Price Prediction Using LSTM RNN, in *Proceedings of Emerging Trends in Expert Applications and Security*, pp 493–503.

Prasanna, S and Ezhilmaran, D, 2013. An analysis on stock market prediction using data mining techniques, *International Journal of Computer Science and Engineering Technology*, 4(02):49–51.

Shah, D, Isah, H and Zulkernine, F, 2019. Stock market analysis: A review and taxonomy of prediction techniques, *International Journal of Financial Studies*, 7(2):26.

Sureshkumar, K and Elango, N, 2012. Performance analysis of stock price prediction using artificial neural network, *Global Journal of Computer Science and Technology*.

Wellmer, F W and Scholz, R W, 2017. Peak minerals: What can we learn from the history of mineral economics and the cases of gold and phosphorus?, *Mineral Economics*, 30(2):73–93.

Wright, G and Czelusta, J, 2003. Mineral resources and economic development, *Conference on Sector Reform in Latin America, Stanford Center for International Development*, pp 13–15.

Yu, S S, Chu, S W, Chan, Y K and Wang, C M, 2019. Share Price Trend Prediction Using CRNN with LSTM Structure, *Smart Science*, 7(3):189–197.

Discrete vein modelling – implications of a novel geology driven resource estimation methodology for vein hosted mineral deposits

M Munro[1] and J P van Dijk[2]

1. Technical Director, GMEK, Gold Coast Qld 4227. Email: michael.munro@gmek.com.au
2. Principal Geologist, OCRE, The Hague, Netherlands. Email: janpietervandijk@live.com

ABSTRACT

Discrete vein modelling presents an innovative geology driven 3D modelling method for quantification of vein hosted mineral deposits, with far reaching potential for critical mineral supply and low impact resource extraction. By integrating key geological drivers with advanced discrete fracture network modelling, the DMX protocol (launched in 2019) converges to a more realistic representation of complex vein systems in three-dimensional space. The approach insights greater geologic reasoning in distributing mineral grades where vein boundaries are already defined. This presents a viable alternative to existing modelling and estimation methods and has important implications for mineral resource estimation and reporting. Further implications are discussed, where the enhanced understanding of complex orebody characteristics can potentially be used in optimising mining and mineral processing, supporting more sustainable and efficient mining practices.

INTRODUCTION

Veins, mineral-filled fractures, are a key data set providing a visible record of fluid flow and mineral transport in fractured rock systems. They are also an important source of critical and rare minerals. However, their geologic complexities present significant challenges to resource evaluation.

Many vein deposits are characterised by discontinuous and narrow veins, typically less than 2–3 metres wide, which can be particularly challenging to spatially constrain, especially with limited drill spacing. The complex nature of these vein systems has been discussed extensively over years (eg Hulin, 1929; Dominy *et al*, 1999), where veins can exhibit variable geometric properties (eg orientation, size, thickness), branching behaviour, and interactions with other fracture sets or geological features.

Despite advancements in understanding mineralised vein systems, significant errors in resource estimation persist. The problem is widely recognised, sharing several recurring issues identified with modelling complex orebodies generally. These include the underutilisation of available structural data and challenges in integrating structural data from different sources (Wellmann and Caumon, 2018; Cowan, 2020; Vearncombe, 2023). Additionally, deterministic methods often fail to account for inherent variability (Dominy *et al*, 1999; Grose *et al*, 2019), and both explicit and implicit modelling methods tend to oversimplify, lacking realism as they are constrained by geology and grade statistics rather than the structures controlling mineralisation. Furthermore, there is a notable lack of methods to integrate structural patterns and key dependencies into interpolation and modelling processes (see Cowan, 2020; Vearncombe, 2023).

For decades, discrete fracture network (DFN) technology, well described by Lei, Latham and Tsang (2017), has provided capabilities to incorporate structural observations for generating probabilistic distributions of discrete fractures, including mineral filled fractures (veins). However, major issues exist in the use of simplified fracture distributions with predominantly model-driven DFN technologies in use, which fail to define the key geologic dependencies and drivers to mimic the observed vein distributions. In addition, fractures are modelled as flat 2D features in space (not 3D volumetric veins), they are always intersecting, models often lack adequate domaining, and fail to integrate deterministic data directly into the modelling.

In recent years, a new data-model driven protocol (DMX), introduced by van Dijk (2019, 2020), has been developed to converge towards a more realistic representation of discrete fractures and veins in space. The protocol integrates more observed vein data into the model and honours key geological relationships that govern vein distributions for a more realistic representation (Figure 1). Veins are modelled in 3D with geometric properties and dependencies, which can be derived from analysing various data sources across the scale range (from mm to km). Ordinarily, these include mapping of outcrops or excavations, and borehole inputs, where televiewer data is most practical.

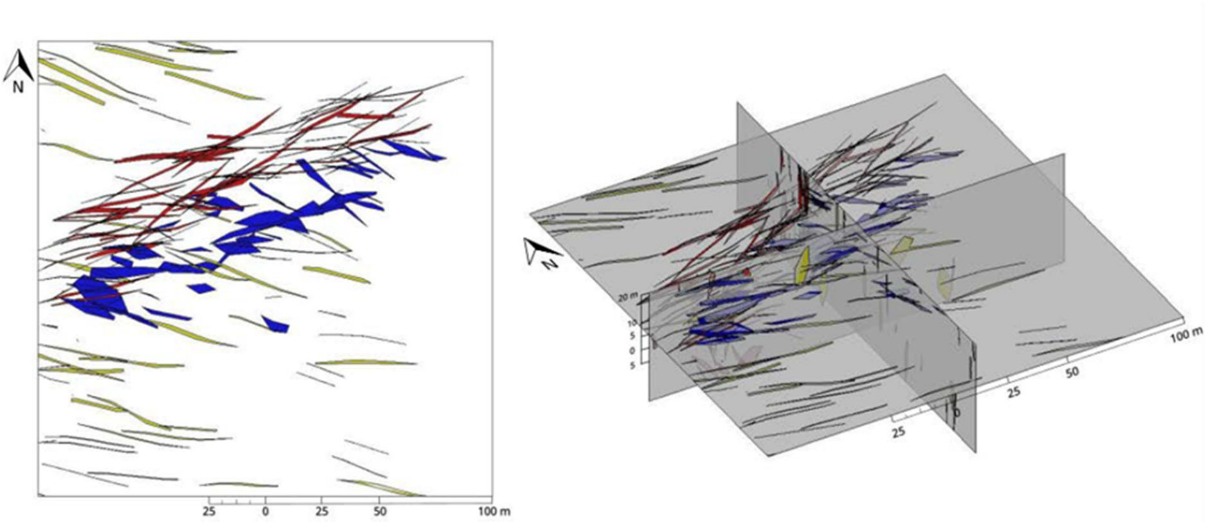


FIG 1 – Multi-section view of discrete vein model built using the DMX protocol.

Additionally, the technology known as Fracture Potential and Domain Mapping (FPDM), as defined by van Dijk (1998), is utilised to aid in identifying spatial domains based on vein density and orientation. Where sufficiently dense data sets are also available, DMX can integrate the interconnections between observed features, introducing them as deterministic elements in the model. This technology is particularly critical for drilling, as it employs probabilistic conditioning based on the geometric properties observed with the veins (size, thickness, orientations, and number/frequency).

This can address limitations with aspects of traditional interpolation (discussed by Sullivan, 2021; Cowan, 2022), by establishing best-fit planes between drilling intercepts driven directly by structural observations. In addition, interpolations can be conditioned by scale dependent relationships (eg length versus width), and by what are defined as geologic dependencies (eg truncations, van Dijk, 2020). As discussed by Vearncombe (2023), these types of relationships controlling the spatial anisotropy cannot otherwise be described with spatial-statistical methods often used.

GRADE DISTRIBUTION

The available modelling presents geologists with new opportunities to constrain estimates using the structures hosting the mineralisation for more complex vein deposits. This can include mineralised veins narrower than typical sample lengths used in drilling investigations, which often fail to reflect the true grade characteristics (see Dominy *et al*, 1999).

The grades can be distributed across veins using a wide range of methods. Initially, these may involve partitioning the data into domains or sets with different populations, or more complex distributions and relationships where multiple phases are superimposed for example. Importantly, this presents new opportunities to integrate less-conventional data sources in estimation, using the information to assign mineral grades closer to how they were developed within a dynamic system. This includes vein data from thin sections and fluid inclusions, which are the only direct record of fluid flow and mineral transport in the rock mass.

Grades can be assigned deterministically or estimated through probabilistic simulations, such as sequential Gaussian simulation (SGS), which is used frequently with DFN modelling in other industries. Figure 2 includes an example where the simulation is conditioned to known data points from drill hole assays. Resource geologists can justify their choices based on observations, available data, the required level of investigation, and other factors.

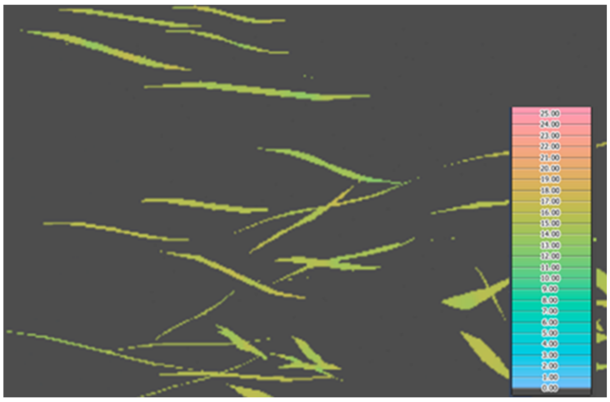


FIG 2 – Conditional simulation of mineral grades (Au g/t) across discrete vein structures in Vulcan.

RESOURCE ESTIMATION

Following the nomenclature within the Pij system (Dershowitz and Herda, 1992; van Dijk, 1998) the parameter for vein volume, P33, becomes an important metric for resource estimation, where P is the persistence of 3D vein volumes within a 3D sampling region (hence P33). The P33, expressed in%, may be used to characterise select areas, or an entire model. Industry standard block modelling software (eg Deswik or Vulcan) provides further means to obtain volumes from smaller regions using the ore to waste ratio (%) for respective blocks with known volumes. Additionally, the modelled vein volumes and associated grades can be used solely, or in combination with more conventional estimation methods for background mineralogy, such as wall rock alteration or disseminations within the broader host rock.

A simple yet effective validation step is to compare model slices (sections) to available surface analogues/outcrops or mine exposures. This is to confirm the veins distribution, and to check the output vein patterns honour the geologic drivers controlling the distributions (eg fold/tilt relationships, terminating behaviours etc). A quantitative approach to validate the veins distribution can assess P21 for select slices (measure of 1D veins within a 2D section area), or P22 (% 2D vein area within a 2D section). Note with the latter, consideration should be given to the angle of the viewing plane with respect to the veins aspect.

Another use in resource estimation is to provide an alternative method to validate other estimation approaches, or *vice versa*. This is also where discrete vein modelling technology in general can serve as an important tool for validation. For instance, consider a 3D cube where discrete vein modelling is applied to generate a fixed simulation for a complex vein system, where the vein boundaries and grade distributions are easily interrogated. Using the same source data, we may then apply alternative modelling methods, and simply view and compare the outputs to understand how each performs.

Implications for reporting

Discrete vein modelling has immediate implications for reporting mineral resource estimates. First, the various modelling inputs, outlined in van Dijk (2019), include the geometric properties of the veins and mathematical functions to define the various distributions and dependences used to create the models. Compared with spatial-statistical inputs such as variogram parameters, these provide more tangible parameters for geologists to demonstrate, and clearly describe how they have arrived at their assumptions around geologic continuity. Similarly, this may also facilitate the validation process during independent reviews.

The demonstration of grade continuity, in part, goes hand-in-hand with the geologic continuity where grades can first be distributed to the individual ore shoots/veins. Additional methods and modifying factors used to distribute grades may then be described. Where the veins boundaries are already defined, this may foster greater geological reasoning to justify how grades are distributed among them, since there is already less reliance on spatial-statistics to describe the anisotropy.

As is readily apparent in discrete vein modelling, certain structural information that is often overlooked in modelling (eg geologic dependencies such as vein intersecting behaviours or layer/unit dependencies) may significantly influence the overall vein distribution. Including this type of information can be more impactful than simply adding more drilling intercepts for example. Therefore, mineral reporting codes may benefit from more prescriptive guidelines in these areas.

Where applicable, the use of discrete vein modelling as an alternative method for estimation may also offer greater confidence in reporting. This is where, in some instances, comparing it to a fundamentally different approach may be more advantageous than comparing similar methods that share the same primary limitations, such as two derivative geostatistical methods.

MINING IMPLICATIONS

While the process of discrete vein modelling invariably incorporates probabilistic elements in generating the veins distributions, the available model outputs retain important characteristics. These include a more accurate representation of the veins geometric properties and interacting behaviours in 3D space. This is compared to conventional modelling methods, including those more reliant on spatial-statistical trends of mineral grades.

The available information has important benefits where mining and processing activities can potentially be optimised based on an increased understanding of the orebody characteristics (namely vein geometries and ore to waste ratios). This could include; optimising equipment sizing to minimum mining widths, adopting more targeted mining methods, or optimising processing methods for example.

The range of potential benefits may include:

Mining:

- Reduction in mined waste (rock breaking and haulage)
- Reduced development and associated footprint
- Reduced dumping footprint or backfill requirements
- Reduced water consumption
- Reduced energy consumption and emissions

Processing:

- Reduced waste processing (crushing and beneficiation)
- Increased ore recoveries
- Reduced processing waste (dry or tailings)
- Reduced processing waste footprint
- Reduced water consumption for wet processing
- Reduced energy consumption and emissions

Where applicable, implementing discrete vein modelling offers immediate financial and environmental benefits where any of the above points can be realised. Additionally, the refined orebody models can reduce missed opportunities by enabling more accurate evaluations of vein deposits and provide new insights to revisit previously overlooked resources.

CONCLUSIONS

Discrete vein modelling offers a transformative approach to capturing and modelling the complex characteristics of vein-hosted mineral deposits. By integrating structural geology with advanced fracture modelling technology, specifically through the DMX protocol, we can better understand the spatial distribution of key vein hosted mineralisation. This method also promotes a more geologically driven approach to distributing grades and reduces reliance on the ‘black box’ nature of traditional geostatistical methods to aid validation.

As with any tool, discrete vein modelling may be more applicable for some vein deposits than others. It may also be used in conjunction with other estimation methods or serve as robust validation tool to compliment them. Where it can be applied, the available orebody knowledge around the veins geometric and ore to waste characteristics, may provide significant financial and environmental benefits with the optimisation of mining methods and equipment. Thus, discrete vein modelling not only improves the precision of resource estimates but also supports sustainable and efficient mining practices.

REFERENCES

Cowan, E J, 2020. Deposit-scale structural architecture of the sigma-lamaque gold deposit, Canada—insights from a newly proposed 3D method for assessing structural controls from Drill Hole Data, *Mineralium Deposita*, 55(2):217–240.

Cowan, E J, 2022. Structural analysis from drill hole assay data using locally varying anisotropies (LVA)–a catalyst for structural geological enlightenment, *Structural geology and resources*, Kalgoorlie, pp 12–19.

Dershowitz, W and Herda, H, 1992. Interpretation of fracture spacing and intensity, *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, 30(4).

Dominy, S C, Annels, A E, Camm, G S, Cuffley, B W and Hodkinson, I P, 1999. Resource evaluation of narrow gold-bearing veins: Problems and methods of grade estimation, *Transactions of the Institution of Mining and Metallurgy-Section A-Mining Industry*, 108:A52.

Grose, L, Ailleres, L, Laurent, G, Armit, R and Jessell, M, 2019. Inversion of geological knowledge for fold geometry, *Journal of Structural Geology*, 119:1–14.

Hulin, C D, 1929. Structural control of ore deposition, *Economic Geology*, 24(1):15–49.

Lei, Q, Latham, J-P and Tsang, C-F, 2017. The use of discrete fracture networks for modelling coupled geomechanical and hydrological behaviour of fractured rocks, *Computers and Geotechnics*, 85:151–176.

Sullivan, S, 2021. Recognising the impact of uncertainty in resource models, Proceedings of AEGC's 3rd Australasian Exploration Geoscience Virtual Conference [Preprint].

van Dijk, J P, 1998. Analysis and modelling of fractured reservoirs, in *SPE Europec* featured at EAGE Conference and Exhibition, pp SPE-50570.

van Dijk, J P, 2019. The DMX Protocol: A New Generation of Geology Driven 3D Discrete Fault and Fracture Network Modelling, *Adipec 2019 Conference*, SPE-197772-MS, 17 p.

van Dijk, J P, 2020. DMX-FMX: Bridging the Gaps Between Data Analyses and Combined Data–Model Driven 3D Fault and Fracture Network Modeling – A Novel Approach, *Adipec 2020 Conference*, SPE-202850-MS, 17 p.

Vearncombe, J R, 2023. Function and status of structural geology in the resource industry, *Australian Journal of Earth Sciences*, 70(7):908–931.

Wellmann, F and Caumon, G, 2018. 3-D Structural Geological Models: Concepts, methods and uncertainties, *Advances in Geophysics*, 59:1–121.

Enhancing dragline safety – a multi-layered proximity detection system

B Murphy[1]

1. Manager Engineering, Coronado Global Resources Inc, Blackwater Qld 4717.
   Email: bmurphy1@coronadoglobal.com

ABSTRACT

Seeking to reduce the likelihood of uncontrolled personnel entry into the operating footprint of a dragline, Coronado Global Resources initiated a review of proximity detection systems currently available and equipment interactions in and around dragline operational areas. At the time of the assessment, there were no established personnel proximity detection systems in compliance with functional safety standards for large machinery in Australia. Our primary objective was to guarantee a functionally safe outcome, particularly by implementing a performance-level-rated system in accordance with AS4024 (Safety of Machinery series of Australian Standards).

Applying appropriate detection technologies, the goal was to reduce the residual operating risk for machine-to-machine and machine-to-personnel interactions. A comprehensive analysis of available or in-development technologies was conducted, and a layered approach (demonstrated in Figure 1) was adopted to achieve the desired risk reduction by segregating the sensing zones into distinct areas using diverse and disparate technologies consisting of radar (short); light detection and ranging (LiDAR) (medium); and optical (long). To address the potential limitations of each technology, overlapping layered sensing zones were designed. With LIDAR and optical using two distinct artificial intelligence (AI) systems to classify detections, these were specifically trained to handle the unique environments of a mining operation.

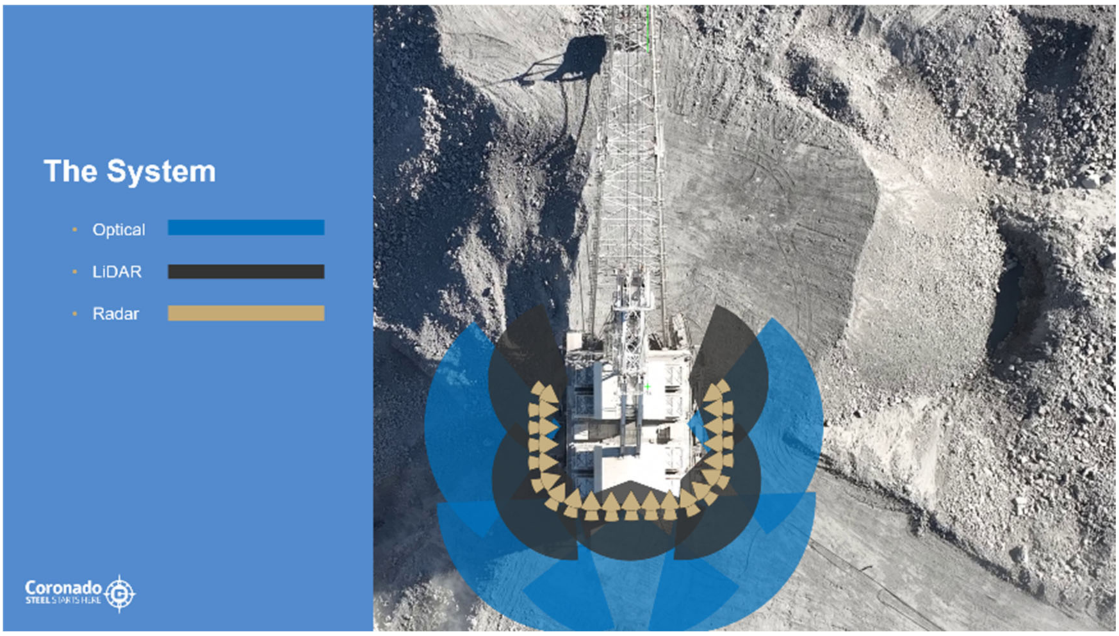


FIG 1 – Dragline Proximity Awareness layered sensing zones. Source: Property of Coronado Curragh Pty Ltd. Not for further distribution or reuse.

Criticality and urgency increases as the proximity to the dragline decreases. Optical sensors provide notifications enabling operators to track personnel/vehicles around the dragline; the LiDAR alerts the operator and proportionally reduces the swing reference depending on the distance of the detection from the dragline; and the radar removes the swing function entirely, further alerting the operator and locking out the swing functionality with reset procedures.

This paper details more information about the project, which effectively reduces the risk of personnel/equipment interactions with draglines through reliable detection and failure mode design.

The versatility of this scalable approach makes it applicable to other machinery within the mining industry where similar risks exist.

INTRODUCTION

Coronado Global Resources operates four draglines in its fleet, located at its Curragh mine in Queensland. Curragh is an open cut mining operation, where coal extraction involves removing the overburden from the top down. Typically, open cut mines are excavated on benches, which represent vertical levels of the pit. The height of the benches is determined by the machinery used to remove the overburden or product. It is in this context that the draglines operate.

Draglines can be seen as simple machines however engineering challenges arise due to their scale, which often push boundaries of material science. Coronado's largest machine, the Marian 8750, has buckets that can typically lift 220 t per cycle. It can lift material from 65 m below ground level and throw it 60 m above ground. The boom is 100 m long, weighing 6800 t. Coronado achieves a typical cycle rate (dig, lift, swing to spoil, dump, swing to dig face) of 80 secs while running off an extension cable that delivers up to 20 megawatts (MW) of power from the grid.

The safety of personnel and equipment around heavy machinery in the workplace is the priority. Traditional operational methodologies or procedures may not provide operators with sufficient awareness of nearby personnel or equipment, creating potential risks. Currently, there is no solution in the market for a dragline that can be considered functionally safe according to recognised standards. In everyday terms, this means that everything has single points of failure or is strictly controlled administratively, which is the lowest control measure when considering the hierarchy of controls.

The Proximity Awareness System (PAS) aims to be an engineering control that addresses these challenges. It automatically notifies operators and takes appropriate action when personnel or equipment enter the defined operational zone around the machines, typically within the boom point. This system ensures a higher level of safety and minimises the risk of accidents in the mining environment.

PRODUCT OVERVIEW

The PAS is a dragline-centric solution, which means all components are contained within the machine and do not require external connectivity or computation. Coronado's approach involved implementing three discrete systems with overlapping sensing areas, which were integrated into a single user interface for ease of use.

Each system had its own design and deployment criteria and requirements, but they were all developed in parallel to ensure the shortest possible time frame for completion. Coronado primarily used off-the-shelf parts readily available in Australia, ensuring easy maintenance and cost-effectiveness. This system is designed for scalability, making it easy to implement across its draglines.

Project approach

Coronado embarked on its dragline project journey in early 2022 through an ideation phase with multiple internal and external parties involved. The conversation was premised around current state of machine learning and methods of achieving a functionally safe outcome.

Given time constraints, the only viable approach was to pursue parallel paths. These paths included camera development, LIDAR development, radar development, functional safety development, software integration, human-machine interface (HMI), and infrastructure. In total, eight distinct and interwoven paths were pursued, with the main focus on sensor validation and deployment.

Challenges

Challenges, both obvious and hidden, include the scale of a dragline, as sensing zones that covered a large area around the machine needed to be designs. Additionally, complexities related to edge computation arose, as the system needed both the availability and raw computation power to process the large amount of data produced by the sensors and consumed by the algorithms.

Another challenge was the state of machine learning, as the aim was to create a system that was easy to deploy and maintain. Given that the system would be operating in an industrial environment, it was crucial to ensure that the sensors used were rated for such conditions.

To achieve the system outcome that is compliant with the relevant safety standards, such as AS4024, these challenges were carefully considered and addressed throughout the project to ensure the successful implementation. Lastly, a significant challenge faced revolved around user adoption while introducing a new technology during the rollout.

Active optical, LiDar, radar

The basic operational principles of active optical, LiDar, and radar can be simply demonstrated with a boarding procedure. Pretend Person A reaches the camera's active zones (50 m), and Person B is in the chair operating the dragline. Person A's activities are flagged to the operator's cab heads up display, as shown in Figure 2, and the system actively tracks him until the next layer has an event, which is the LiDAR (25 m). AI recognises Person A is, in fact, a person. The systems cross-check and validate that a control action is required. The control system starts applying a clamp to the slew reference to reduce the machine's top speed. As Person A steadily approaches the machine, as shown in Figure 3, the clamp is adjusted proportionally until reaching the boarding zone, where the machine stops and Person B confirms that Person A is okay to board. The last action occurs when Person A breaches the radars (5 m), where all slew mechanisms are locked until a reset is completed. As Person A gets onto the machine, he/she verifies that the zone breach is clear and resets the system. The dragline then goes back to work. The system works in reverse for personnel disembarking the dragline.

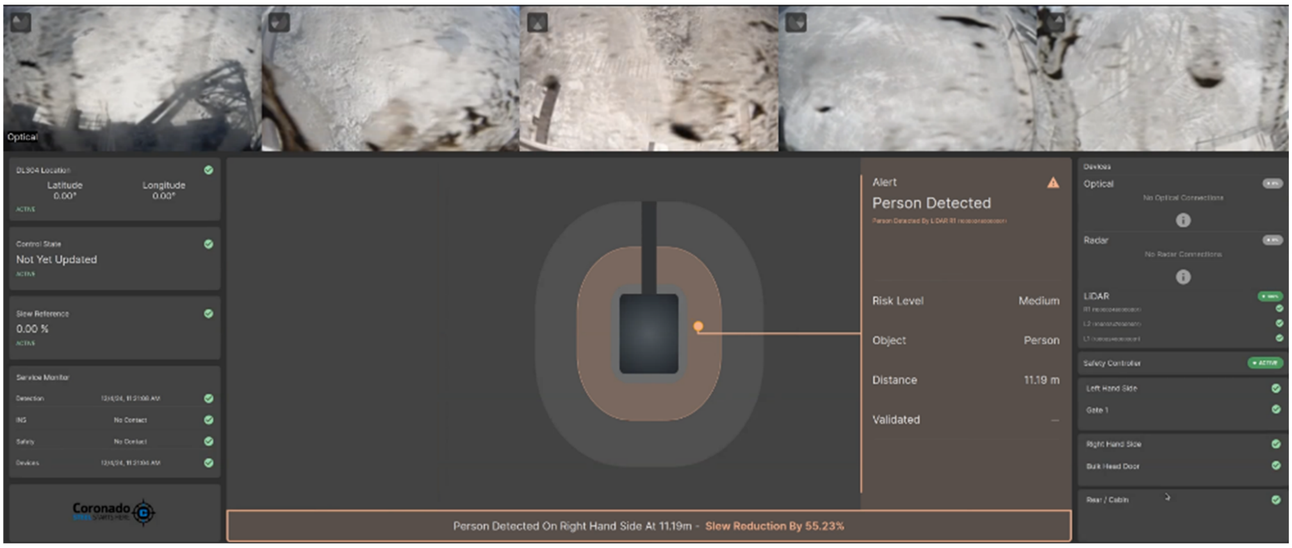


FIG 2 – Dragline Proximity Awareness onboard Head Up Display (HUD) showing a person being detected by the LiDAR system and an active slew clamp being applied. Source: Coronado Curragh Pty Ltd. Not for further distribution or use.

FIG 3 – Dragline Proximity Awareness being triggered by a person entering the operational zone during validation process/commissioning. Source: Coronado Curragh Pty Ltd. Not for further distribution or use.

Features/factors of the simple and diverse approach of the PAS include:

- Three distinct systems that have overlapping device sensing areas.
- All design, procurement of commentary and system validation was undertaken in parallel to achieve the shortest time frame for completion.
- Dragline centric – all componentry is within the dragline operational systems and does not require external connectivity.
- Compliant Performance Level Rating (PL as per AS4024) – working with engineering partners to achieve the desired safety ratings for equipment.
- No single failure modes (includes system redundancies).
- Ability to scale out across dragline – copy and paste between draglines (within reason).
- Minimal downtime for installation – used dragline maintenance down days and specific outage for tie in.
- Every step has a validation gates process to complete before progressing (Across all sensing systems).
- Off the shelf parts – available in Australia.

CONCLUSION

The Proximity Awareness System (PAS) is a simple and robust proximity awareness system that notifies the operator to take an appropriate action automatically when personnel or equipment enter the operational areas of the machines. Coronado Curragh mine set out to provide an engineered solution to the problem for the slew mechanism of a dragline (in line with AS4034). This system ensures a higher level of safety and minimises the risk of accidents in the mining environment.

A deep learning based approach for roof bolt recognition in 3D point cloud of underground mines

D Patra[1], B P Banerjee[2] and S Raval[3]

1. PhD Fellow, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: d.patra@unsw.edu.au
2. Lecturer, Remote Sensing and Geospatial Sciences, University of Southern Queensland, Toowoomba Qld 4350. Email: bikram.banerjee@unisq.edu.au
3. Associate Professor, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: simit@unsw.edu.au

INTRODUCTION

Roof bolts are an essential component of roof support systems in underground mines. They are used to provide structural support to the roof of the mine and prevent it from collapsing. Therefore, it is imperative to perform regular assessments of these roof bolts to avert any hazards. Manual investigations of roof bolts are done by surveyors in underground mines, which is extremely time-consuming and challenging due to the low-light conditions in underground mines accompanied by stringent mine access rules. To this end, automated recognition of roof bolts in 3D point cloud data obtained through laser scanning in underground mines serves as a potential solution to aid roof bolt monitoring. With the continuous advancements in laser scanning-based 3D data acquisition systems, the feasibility of making such surface estimations from 3D point cloud data has increased severalfold.

Where previous studies have used feature engineering and traditional machine learning-based approaches for the detection of roof bolts, this study, for the first time, explores the viability of using a deep learning-based approach for the classification and segmentation of roof bolts within 3D point cloud data, obtained via laser scanning in underground mines. The methodology involves learning features from the point cloud data and distinguishing between roof bolts and other elements. The deep learning model evaluated for this purpose undergoes thorough training, testing, and validation using data acquired from a mining site. To assess the effectiveness of this approach, its outcomes are compared against manually collated ground truth data and an eigenvalue-based feature engineering approach. Additionally, standard segmentation metrics such as intersection over union and precision are employed to evaluate the approach's quality. Implementing this automated approach could substantially enhance the safety of underground mining operations by offering a more reliable and efficient means of roof bolt detection.

DISCUSSIONS

Most research on roof bolt identification in 3D point clouds relies on feature engineering and traditional machine learning-based approaches for the detection of roof bolts. However, the current techniques in the literature face certain limitations. Many of the modern roof bolt identification methods rely on local point descriptors to exploit the cylindrical nature of the exposed sections of a roof bolt (Saydam *et al*, 2021). However, in doing so, such algorithms face difficulties in accurately identifying the face plates, especially their edges (Singh, Raval and Banerjee, 2021, 2020). Monitoring and identifying the face plates of the roof bolts is as important as monitoring the roof bolts themselves since their condition is necessary for analysing the stability of the bolt and the underlying rock mass. On the other hand, in machine learning-based bolt identification approaches, the feature descriptor sets for classification need to be manually determined. One of the studies has used as many as a 64-dimensional feature descriptor vector for feeding into their neural network (Gallwey, Eyre and Coggan, 2021). However, using multiple features has little to no implications for efficiency since most of the features can exhibit similar characteristics for both bolt and non-bolt points.

To overcome these limitations, a deep learning-based roof bolt identification and segmentation algorithm is proposed and evaluated. Although there has been significant progress in deep learning-based semantic segmentation of point clouds (Zhang *et al*, 2023; Xie, Tian and Zhu, 2020), limited research has been undertaken to utilise those models in the context of roof bolt identification. Such models have the inherent ability to identify feature vectors for associating classes and labels with points. Unlike other machine learning algorithms, they don't require manual feature definition. Furthermore, when applied to the point clouds, the segmentation process is capable of accurately identifying the roof bolt face plates along with the cylindrical exposed sections of the roof bolts.

The point clouds including roof bolts need to undergo certain preprocessing steps before they can be used to evaluate and train the segmentation model. The point clouds are first translated to the origin followed by labelling the points as 1 and 0 for bolts and non-bolts respectively, based on the ground truth data. These point clouds are then used to train, test, and validate our deep learning segmentation network based on PointNet++. PointNet++ is a deep neural network model on 3D point cloud data that can approximate and learn features for any continuous set function, thereby being able to identify objects of any shape given enough training data (Qi *et al*, 2017). Investigations on the deep learning model show promising results for semantic segmentation.

After training the model on the labelled original point cloud, without applying any filtering steps, the results reached a respectable mean intersection over union (IoU) of 86 per cent (71 per cent IoU for bolt points) and a precision of 91 per cent. The results have been compared against the ground truth data and an eigenvalue-based feature engineering approach as can be seen in Figure 1. After analysing several eigenvalue features like planarity, omnivariance, curvature, pointness, curveness, and surfaceness, the curvature threshold-based approach was selected for the comparison since it stood out to be the most prominent feature engineering approach for accurately identifying the cylindrical protrusions, ie roof bolts, in a point cloud. From the figure, it is evident that although the eigenvalue-based approach can accurately identify the cylindrical protrusion of the bolts, it lacks the ability to identify the face plate of the bolts. On the other hand, the deep learning approach can accurately identify the bolt protrusions along with its face plate, proving to be a superior and efficient approach.

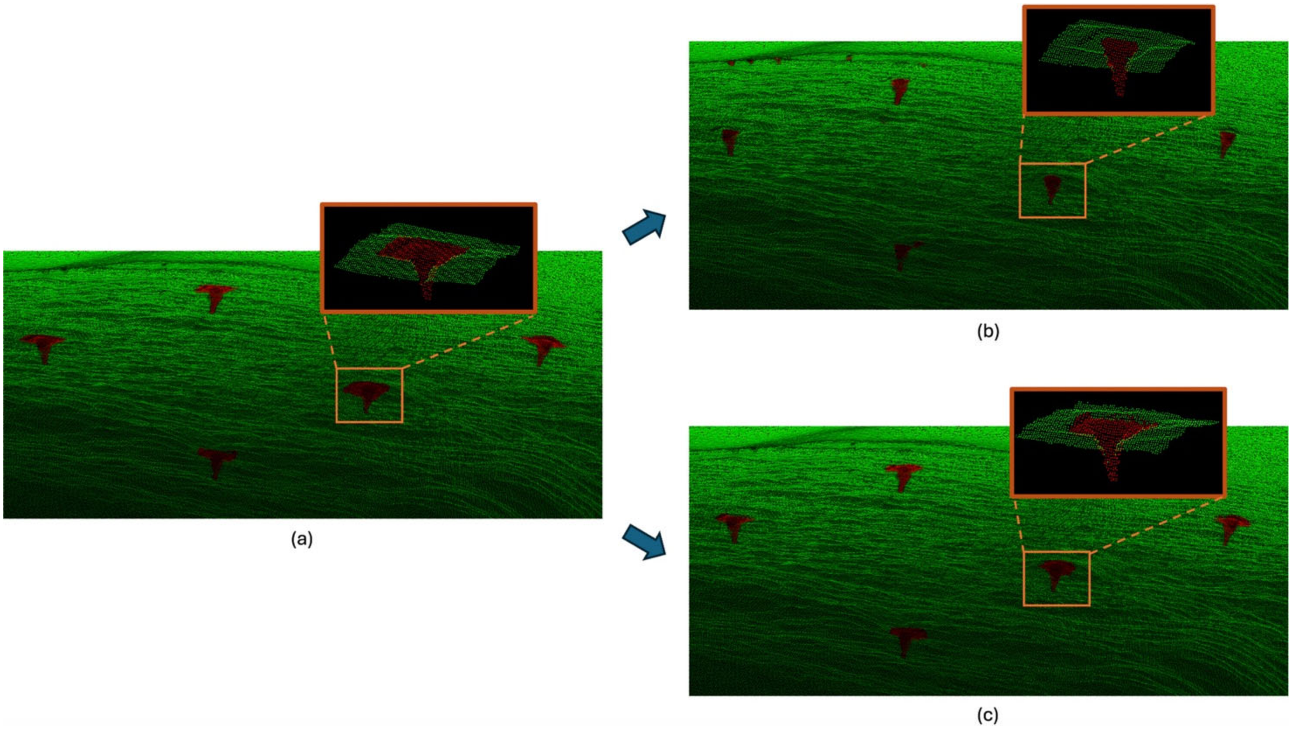


FIG 1 – (a) Ground truth roof bolts, (b) Predicted roof bolts using eigenvalue feature, and (c) Predicted roof bolts using deep learning approach.

Roof bolts are extremely small objects when compared to a large-scale underground mine scenario and most of the 3D point cloud consists of non-bolt points with only an extremely tiny proportion of roof bolt points. In the future, the results of the deep-learning approach can be further enhanced by tuning the input with more enhanced preprocessing steps. It has been found that eigenvalue feature-based roof bolt identification has a very high recall rate. Hence it can be used as a preprocessing step to filter out most of the non-bolt points, thereby increasing the proportion of the bolt points in the point cloud and turning the problem of segmenting tiny roof bolts in a large-scale point cloud into a fairly standard semantic segmentation process. Based on the preliminary results from the deep learning model, it is safe to assume that, after applying such filtering steps, the results can be improved significantly.

REFERENCES

Gallwey, J, Eyre, M and Coggan, J, 2021. A machine learning approach for the detection of supporting rock bolts from laser scan data in an underground mine, *Tunnelling and Underground Space Technology,* 107:103656.

Qi, C R, Yi, L, Su, H and Guibas, L J, 2017. PointNet++: deep hierarchical feature learning on point sets in a metric space, Proceedings of the 31st International Conference on Neural Information Processing Systems (Curran Associates Inc).

Saydam, S, Liu, B, Li, B, Zhang, W, Singh, S K and Raval, S, 2021. A Coarse-to-Fine Approach for Rock Bolt Detection From 3D Point Clouds, *IEEE Access,* 9:148873–148883.

Singh, S K, Raval, S and Banerjee, B, 2020. Roof bolt identification in underground coal mines from 3D point cloud data using local point descriptors and artificial neural network, *International Journal of Remote Sensing,* 42:367–377.

Singh, S K, Raval, S and Banerjee, B, 2021. A robust approach to identify roof bolts in 3D point cloud data captured from a mobile laser scanner, *International Journal of Mining Science and Technology,* 31:303–312.

Xie, Y, Tian, J and Zhu, X X, 2020. Linking Points With Labels in 3D: A Review of Point Cloud Semantic Segmentation, *IEEE Geoscience and Remote Sensing Magazine,* 8:38–59.

Zhang, R, Wu, Y, Jin, W and Meng, X, 2023. Deep-Learning-Based Point Cloud Semantic Segmentation: A Survey, *Electronics,* 12.

Towards a mining metaverse – spatial computing meets digital twins for remote operations

J Qu[1], M S Kizil[2], M Yahyaei[3] and P Knights[4]

1. PhD, The University of Queensland, School of Mechanical and Mining, St Lucia Qld 4072. Email: juncong.qu@uqconnect.edu.au
2. MAusIMM, Associate Professor, The University of Queensland, School of Mechanical and Mining, St Lucia Qld 4072. Email: m.kizil@uq.edu.au
3. Professor, The University of Queensland, Julius Kruttschnitt Mineral Research Centre, Indooroopilly Qld 4068. Email: m.yahyaei@uq.edu.au
4. MAusIMM, Professor, The University of Queensland, School of Mechanical and Mining, St Lucia Qld 4072. Email: p.knights@uq.edu.au

INTRODUCTION

Digital Twins (DTs) are transforming business operations across many industries through their accurate representations of physical entities enabled by IoT technologies. By integrating real-time data analytics and artificial intelligence, DTs can provide valuable insights for decision-making, such as predicting failures before they occur, optimising processes, and enhancing performance which in turn, deliver tangible values to businesses around the world (Lu *et al,* 2020). DTs have been successfully applied in various sectors, such as manufacturing, aerospace, and the building industry, to transform their business operations and create competitive advantages in the face of the fourth industrial revolution (Liu *et al,* 2019) with the number of DT-related publications increasing exponentially since 2017 (Figure 1).

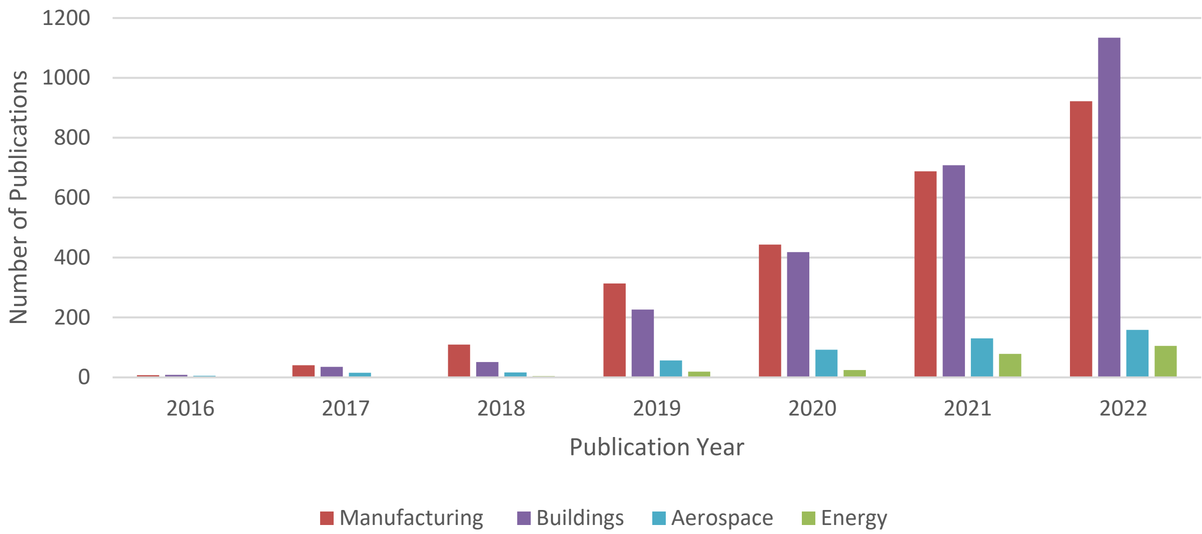


FIG 1 – Distribution of DT literature by industries (Kukushkin, Ryabov and Borovkov, 2022; Qu *et al,* 2023).

However, the minerals industry has not embraced the full potential of digital twins, especially in terms of incorporating effective visualisation and intuitive user interaction designs to maximise the fidelity, usability, and scalability of cyber-physical systems. Since 2017, the mining industry has seen a significantly small number of publications from relevant research. From which, an even smaller percentage of works demonstrated actual bi-directional data integration (Figure 2).

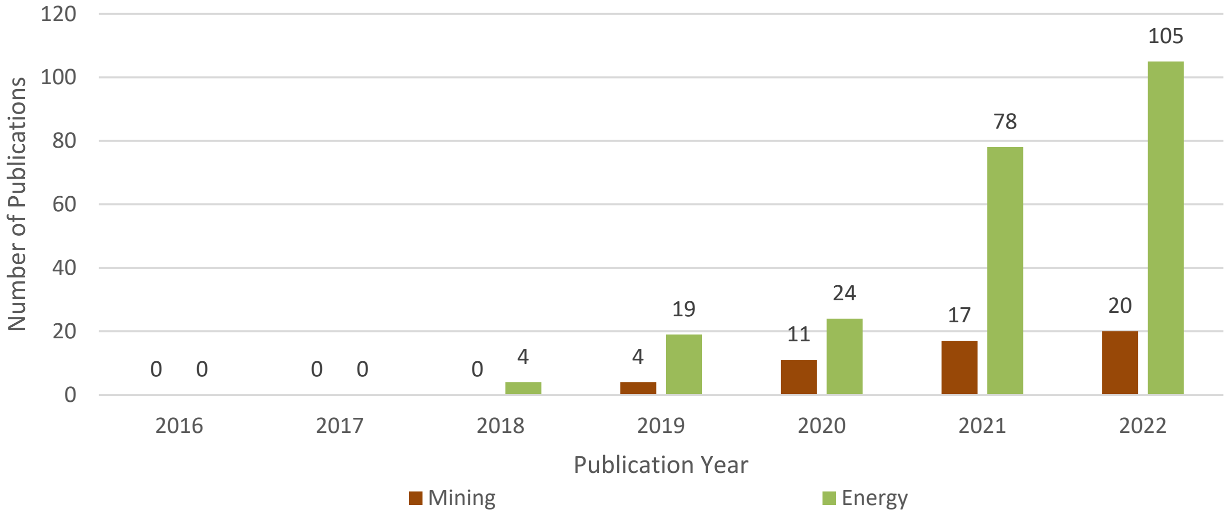


FIG 2 – Numbers of DT literature in the mining industry (Qu *et al,* 2023).

One promising way to address this gap is by leveraging spatial computing technologies, which enable immersive and interactive experiences in virtual reality (VR) (Schofield, Denby and McClarnon*,* 1994). VR can also facilitate the creation of an industrial metaverse for mining-related applications, where users can collaborate and perform real-world tasks in a shared, persistent virtual space from different locations (Stothard, 2023). To demonstrate the feasibility and benefits of this approach, this work presents a proof of concept by developing and deploying a digital twin with real-time monitoring and control capabilities for a legacy ball mill operation, a common type of processing equipment used in the minerals industry. The paper also shows how VR can be used in a cyber-physical system for remote operation and crisis management using software platforms that are widely used in serious game developments (Figure 3).

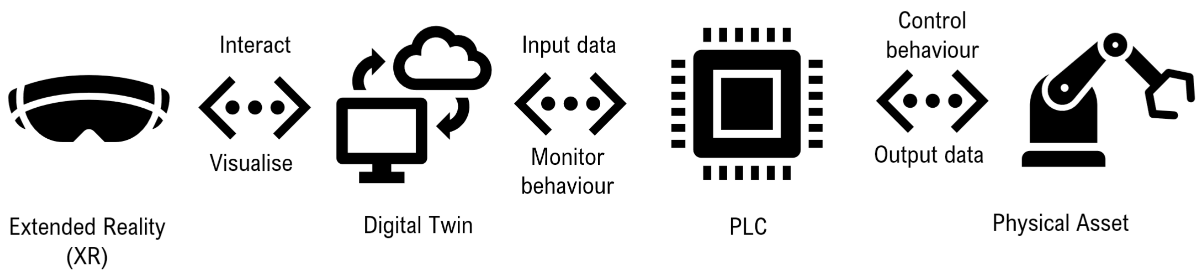


FIG 3 – DT for real-time monitoring and control in XR (Qu *et al,* 2024).

INSTRUMENTATION AND CONTROL

Digital twins have shown extraordinary capabilities in meeting the needs of many industries in improving production efficiency, safety, and reliability. With the boom of Industry 4.0 characterised by the Internet of Things (IoT), cloud computing, and artificial intelligence, a DT with bi-directional data integration can technically not only reflect the current state of physical entities in digital formats but also influence the real world from the virtual realm (Kritzinger *et al,* 2018). Practically, the implementation of such a feature may vary from case to case depending on many aspects such as hardware compatibility, cost, and scalability. As an example, the case presented by Qu *et al* (2024) adopted a hybrid approach to create such a DT for a ball mill equipped with legacy OEM data acquisition hardware to maximise scalability while eliminating the cost associated with hardware upgrades (Figure 4).

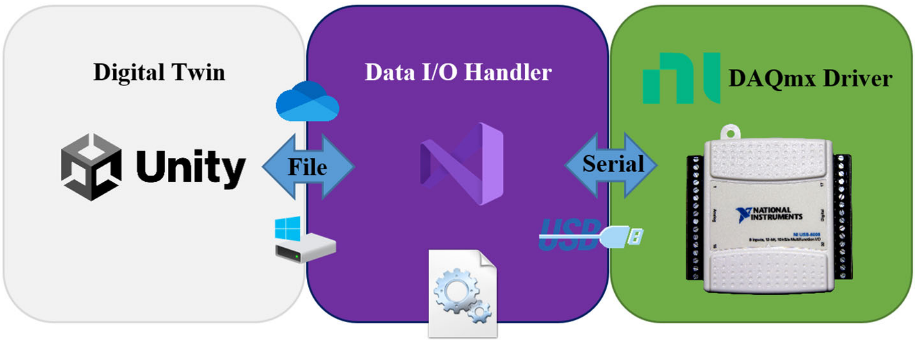


FIG 4 – Bi-directional data integration of a ball mill digital twin (Qu *et al,* 2024).

By deploying the OEM application programming interface (API) in an intermediate data handler application, the DT was able to monitor and control the asset remotely over long distances through a combination of cloud data transfer and local serial bus communication. The data handler application is extremely lightweight, making it exceptionally scalable on micro-sized edge computers that do not require extensive cooling and cost of installation.

VISUALISATION AND INTERACTION

Despite the growing interest in mine digitalisation and automation, the minerals industry retained a human-centred culture from its high emphasis on safety, community engagement, and sustainability both economically and environmentally. With companies such as Meta, Microsoft, and Apple investing heavily in spatial computing technologies such as virtual reality (VR) and augmented reality (AR), complex numerical data can be transformed into digestible information in 3D spaces through sounds, colours, shapes, and motions when paired with digital twins. In the past, VR training had proven its value in the mining sector by eliminating the safety risks associated with on-site training while reducing travel and accommodation costs (Kizil *et al,* 2003). Under the vision of the industrial metaverse, the accommodating role of human operators is highlighted with the introduction of Industry 5.0. A digital twin developed with VR visualisation and interaction in mind allows the user to navigate and operate real-life assets in the virtual space with minimum added training (Figure 5).

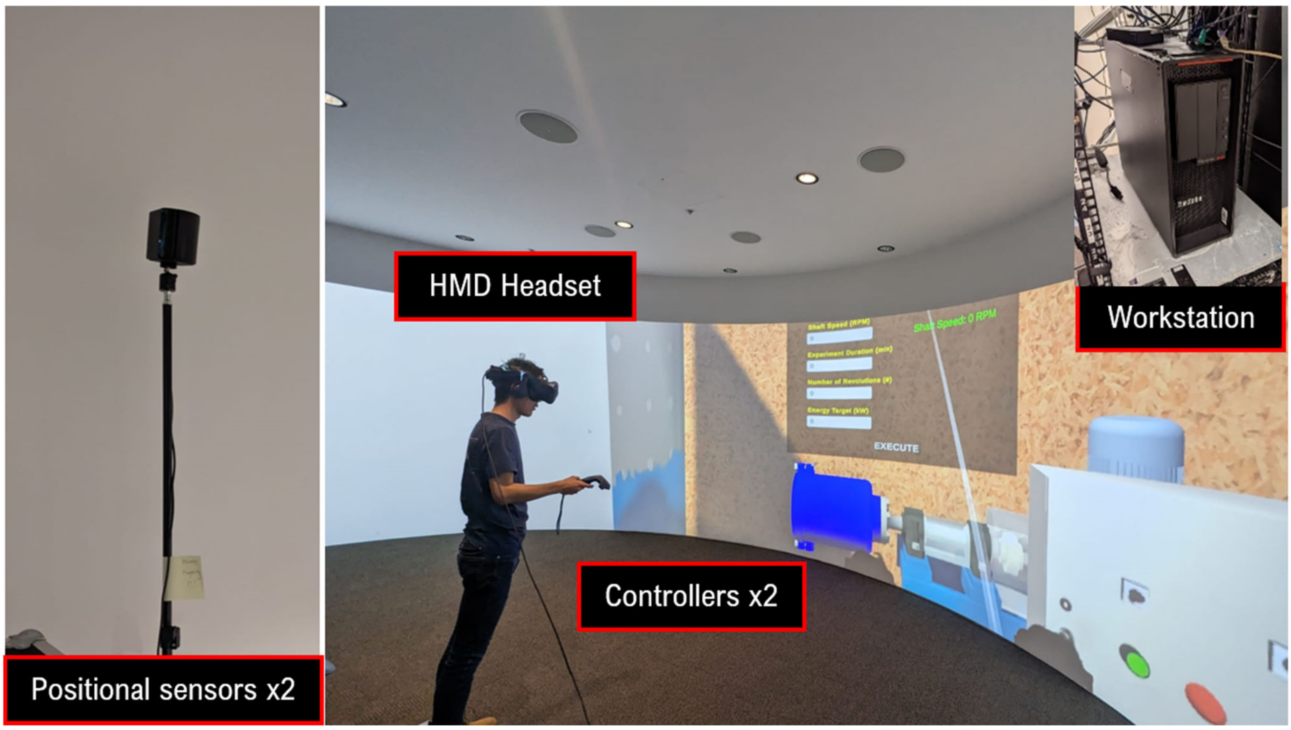


FIG 5 – VR operation with a digital twin (Qu *et al,* 2024).

The Unity format inspired by serious games made the digital twin highly customisable and compatible with the latest developments in the tech market. The presented case adopts the OpenXR standard in its development to deliver seamless locomotion and interaction across all head-mounted displays (HMD) in the market to ensure compatibility and scalability (Figure 6).

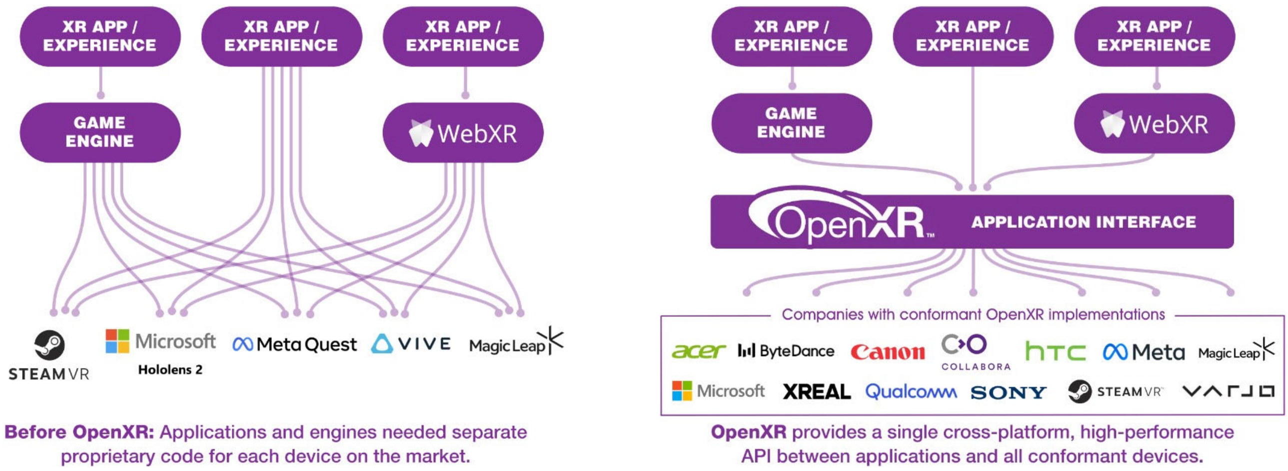


FIG 6 – Advantage of OpenXR in Application Programming (Khronos, 2024).

FUTURE CONSIDERATIONS

While the concept of mining metaverse is still in its infant stage with standing challenges in terms of interoperability, cost, reliability, security, and skill gaps, the International Standards Organisation (ISO) and Standards Australia are working proactively towards creating standards for enabling technologies such as VR, AR, as well as MR (ISO, 2020; Wallace *et al*, 2023). Initiatives from the Institute of Electrical and Electronics Engineers (IEEE) have also recognised the pressing need to develop standards to guide future developments towards different kinds of industrial metaverses (Koziol, 2022; IEEE Digital Reality, 2023). Future developments of DTs and ultimately, the realisation of mining metaverses will need to rely on the joint effort between regulatory bodies, professional societies, research institutes, hardware manufacturers, mining companies, as well as technology providers outside of the conventional supply chain for the mining industry (Figure 7).

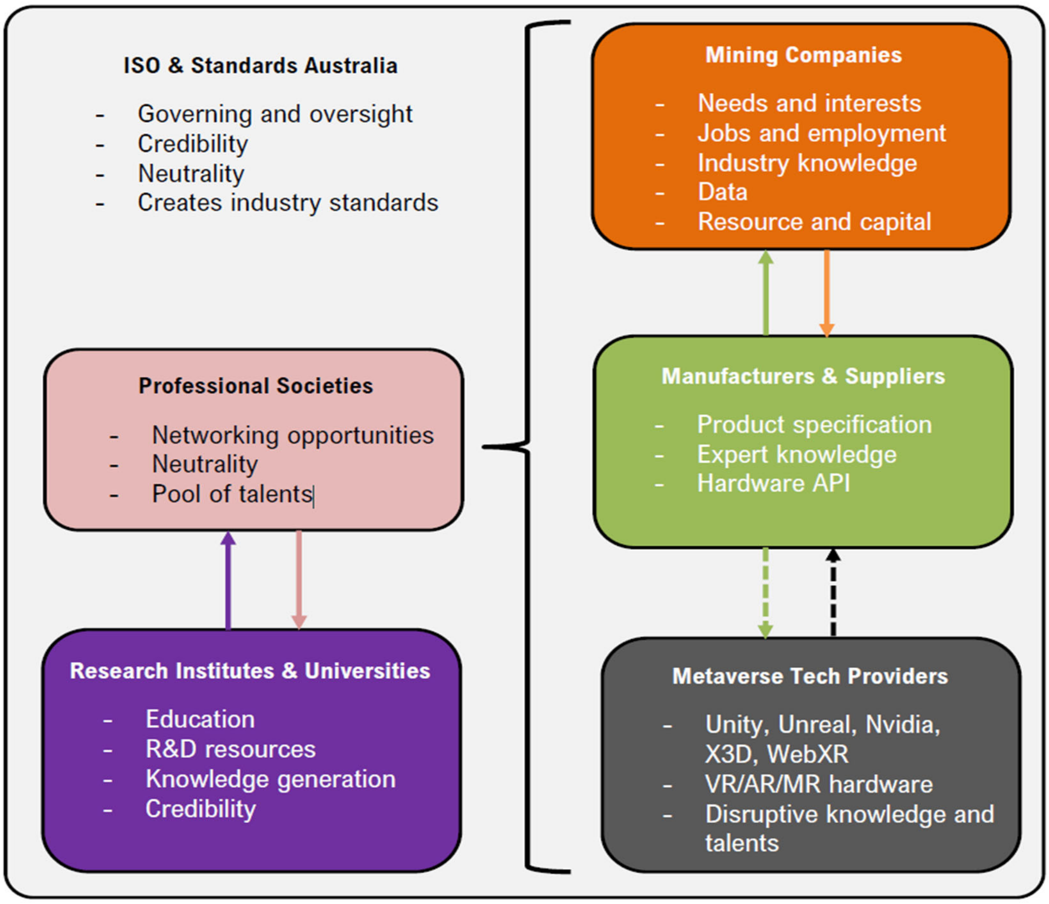


FIG 7 – Industry engagement strategy for mining metaverses (Qu *et al*, 2024).

To realise this vision, the industry needs to take several steps to fully embrace the benefits of DTs. First, the industry needs to invest in the development and adoption of standards and protocols for data exchange, interoperability, security, and privacy among different DT platforms and systems. Second, the industry needs to foster a culture of innovation and collaboration, by engaging with technology providers, research institutes, professional societies, and regulatory bodies, to co-create solutions that address the industry's challenges and opportunities. Third, the industry needs to develop the skills and competencies of its workforce, by providing training and education on DTs and spatial computing technologies, and by promoting diversity and inclusion in the sector. Finally, the industry needs to demonstrate the value and impact of DTs, by showcasing successful use cases, sharing best practices, and measuring key performance indicators. With these challenges overcome, the industry may see a future where companies operate mining metaverses that span across multiple sites, regions, and countries. Mining metaverses would enable seamless integration of data, models, and simulations across the entire value chain, from exploration to closure. They would also facilitate collaboration and communication among diverse stakeholders, such as operators, managers, engineers, regulators, communities, and investors. Mining metaverses would allow users to interact with DTs in immersive and intuitive ways, using VR, AR, or MR devices, depending on their needs and preferences. Users could access real-time information, perform remote control and maintenance, conduct virtual training and audits, and test various scenarios and alternatives. Mining metaverses would also support the industry's sustainability goals, by reducing environmental impact, as well as improving worker safety and well-being.

REFERENCES

IEEE Digital Reality, 2023. IEEE Digital Reality, IEEE. Available from: <https://digitalreality.ieee.org/> [Accessed: 6 Oct 2023].

International Organization for Standardization (ISO), 2020. ISO/IECTR 23842–2:2020. Information technology for learning, education and training — Human factor guidelines for virtual reality content – Part 2: Considerations when making VR content, Switzerland, International Organization for Standardization.

Khronos, 2024. OpenXR: Solving XR Fragmentation, Khronos Group. Available from: <https://www.khronos.org/openxr/> [Accessed: 8 Aug 2024].

Kizil, M S, 2003. Virtual reality applications in Australian minerals industry, in *31st International Symposium on Application of Computers and Operations Research in the Minerals Industries, APCOM*, pp 569–574.

Koziol, M, 2022. The Metaverse Needs Standards, Too - The big players have found a forum but will it make the place come to life any sooner?, IEEE Spectrum. Available from: <https://spectrum.ieee.org/metaverse-standards-forum> [Accessed: 6 Oct 2023].

Kritzinger, W, Karner, M, Traar, G, Henjes, J and Sihn, W, 2018. Digital Twin in manufacturing: A categorical literature review and classification, *IFAC*, 51(11):1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474

Kukushkin, K, Ryabov, Y and Borovkov, A, 2022. Digital Twins: A Systematic Literature Review Based on Data Analysis and Topic Modeling, *MDPI Data*, 7(12):173. https://doi.org/10.3390/data7120173

Liu, Q, Liu, B, Wang, G and Zhang, C, 2019. A comparative study on digital twin models, AIP Conference Proceedings (AIP Publishing).

Lu, Y, Liu, C, Wang K I, Huang, H and Xu, X, 2020. Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues, *Robotics and Computer-Integrated Manufacturing*, 61:101837. https://doi.org/10.1016/j.rcim.2019.101837

Qu, J, Kizil, M S, Yahyaei, M and Knights, P F, 2023. Digital twins in the minerals industry – a comprehensive review, *Mining Technology*: *Transactions of the Institutions of Mining and Metallurgy*, 132(4):267–289. https://doi.org/10.1080/25726668.2023.2257479

Qu, J, Kizil, M S, Yahyaei, M and Knights, P F, 2024. Developing a digital twin for a laboratory ball mill operation – a step towards mining metaverse, *Mining Technology: Transactions of the Institutions of Mining and Metallurgy,* 133(1):1–14. https://doi.org/10.1177/257266682312229

Schofield, D, Denby, B and McClarnon, D, 1994. Computer graphics and virtual reality in the mining industry, *Mining Magazine*, 171(5):284–286.

Stothard, P, 2023. Mining Metaverse – a future collaborative tool for best practice mining, *Mining Technology: Transactions of the Institutions of Mining and Metallurgy*, 132(3):165–178. https://doi.org/10.1080/25726668.2023.2235155

Wallace, C, Rosenberg, L, Pearlman, K and Choudhary, B, 2023. Metaverse standards whitepaper, Standards Australia, Document Number: H2–3061, pp 2–42. Available from: <https://www.standards.org.au/documents/h2–3061-metaversereport>

Advancing slam in underground mines – a unique marker-based approach for enhanced navigation and mapping

P M Ranasinghe[1], B P Banerjee[2] and S Raval[3]

1. PhD student, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: pasindu.ranasinghe@unsw.edu.au
2. Lecturer, Remote Sensing and Geospatial Sciences, University of Southern Queensland, Toowoomba Qld 4350. Email: bikram.banerjee@unisq.edu.au
3. Associate Professor, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: simit@unsw.edu.au

INTRODUCTION

Simultaneous Localisation and Mapping (SLAM) is an important technology that enables autonomous robots to navigate independently and create detailed, real-time maps of their surroundings. This capability is crucial in underground mining settings, where it enhances operational efficiency and significantly strengthens safety in these subterranean environments. SLAM algorithms typically rely on identifying and using distinct geometric features, such as plane and edge features, to understand the spatial layout of the environment and to track how it evolves as the sensor moves through it. In underground roadways, the scarcity of noticeable edge features, coupled with the repetitive nature of walls and corridors, poses a significant challenge, making it difficult for these systems to distinguish one area from another. Furthermore, the absence of global navigation satellite system (GNSS) signals in underground adds more challenges, leading to the accumulation of errors in both the mapping and localisation.

The proposed workflow introduces a robust and precise system with a unique algorithm designed using three sensors: a laser scanner, an inertial measurement unit (IMU), and a camera. To establish the absolute position within the underground space, unique markers are strategically placed and automatically identified. The developed algorithm updates the existing SLAM pipeline to mitigate issues arising from the limited availability of distinct features in underground settings. The system is fully automated, enabling marker identification, georeferencing, localisation, and mapping processes to occur without manual intervention. Advanced image processing techniques are used to detect the positions and identities of the unique markers accurately. Numerical optimisation is used to solve the SLAM problem by organising all incoming data from the sensors into a graph representation. This graph is then optimised to find the appropriate constraints that ensure precise localisation and mapping.

DISCUSSIONS

The data used to develop and test the algorithm is collected from a Livox Avia solid-state LiDAR paired with a machine vision camera. These devices are mounted to share the same field of view, ensuring that both the LiDAR and camera simultaneously record the same scene. This set-up is complemented by the inbuilt IMU in the Livox LiDAR, which captures orientation and movement data, providing an additional layer of details. All sensors are carefully calibrated to ensure that the data from each can be accurately merged, creating a consistent and reliable map.

The captured data set is analysed, and the scan context descriptor (Kim and Kim, 2018) is computed for each LiDAR frame. This descriptor summarises the 3D structural information of the point cloud into a simplified 2D matrix format. Subsequently, the similarity across these neighbouring descriptors is calculated. Results indicate a high similarity between consecutive frames due to the repetitive nature of the scene. This high level of similarity poses a challenge for traditional SLAM algorithms, which may mistakenly interpret these as complete loop closures, thereby failing to generate a comprehensive map.

In the initial stage of developing the algorithm, the plane-to-plane/generalised Iterative Closest Point (ICP) algorithm is programmed and tested to extract features and register consecutive lidar frames (Segal, Hähnel and Thrun, 2009). However, the outcomes are not satisfactory. The Root Mean Squared Error (RMSE), which quantifies the average magnitude of vector distances between matched features across the two-point clouds, is calculated at 0.32644. Additionally, it requires an average of 05 iterations to converge to the final transformation matrix between two-point clouds.

The high registration errors from stitching multiple LiDAR frames necessitated modifications to the generalised ICP algorithm. The updated ICP algorithm now integrates both the XYZ coordinates and the corresponding colour data, which is captured through visual feedback from the camera (Park, Zhou and Koltun, 2017). This enhancement includes a revised distance function that considers both geometric proximity and colour similarity. Additionally, a multiscale strategy has been introduced, where point clouds are initially processed with coarse registration settings and progressively refined to finer details. These modifications allow the ICP algorithm to converge more quickly; for the same data set, it requires only 03 iterations to converge, improving the RMSE to 0.0882—a four times improvement over the traditional algorithm, significantly reducing the cumulative error when stitching all the frames together (Figure 1).

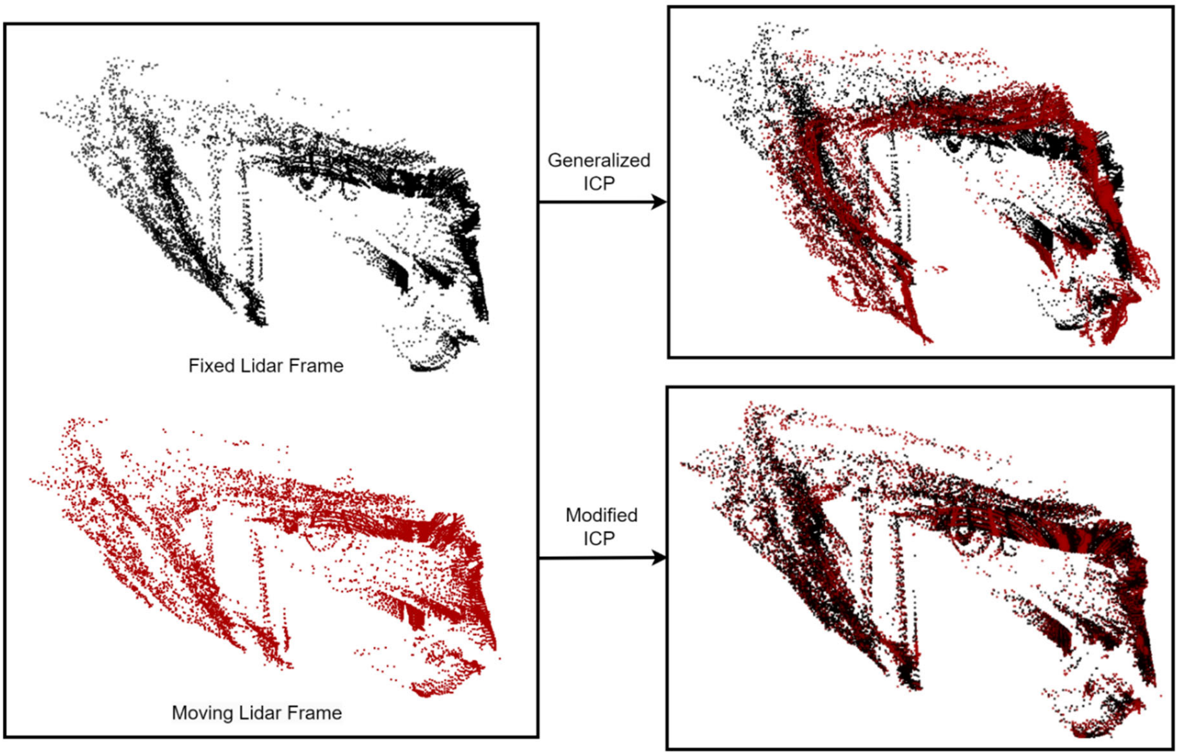


FIG 1 – Comparison of Frame Registration: Generalised ICP Algorithm versus Modified ICP Algorithm.

Before this system can be fully implemented, several key steps need to be completed. The marker identification pipeline needs to be developed. This will use camera feedback to locate markers and precisely position them in the LiDAR frames. The exact coordinates of these markers will then be used to minimise accumulated drift during the construction of the 3D map.

Subsequently, to establish a tightly coupled SLAM solution, all incoming data—from the LiDAR, camera, and IMU, along with the positions of the markers—must be integrated into a graph representation. This graph will then be numerically solved to achieve precise reconstruction of the underground roadways.

REFERENCES

Kim, G and Kim, A, 2018. Scan Context: Egocentric Spatial Descriptor for Place Recognition Within 3D Point Cloud Map, *IEEE International Conference on Intelligent Robots and Systems*, pp 4802–4809.

Park, J, Zhou, Q Y and Koltun, V, 2017. Colored Point Cloud Registration Revisited, *Proceedings of the IEEE International Conference on Computer Vision*, pp 143–152.

Segal, A, Hähnel, D and Thrun, S, 2009. Generalized-ICP, Robotics: Science and Systems V Conference. https://doi.org/10.15607/RSS.2009.V.021

Mining 4.0 initiatives – a pathway to a smarter mining fleet

K Rau[1]

1. CEO, Senzit, Inc., San Jose 95138 CA, USA. Email: karthik.rau@senzit.io

INTRODUCTION

The overall success of a mining operation is directly impacted by the reliability and availability of mining equipment. Heavy-duty vehicles such as excavators and haul trucks are used for conveying of bulk material and improving such assets' availability helps reduce costs, increase throughputs and improve safety (Ravande, 2022). If a mining operation's key performance indicators (KPIs) are tied to operational performance, then overall equipment effectiveness (OEE) is an essential metric to track progress and to identify areas of improvement.

Despite the direct link between fleet OEE and mine performance, the approach to equipment maintenance is still evolving. Metrics including performance parameters (engine hours, engine temperature, air filter condition, oil condition etc) as well as condition parameters need to be tracked to enable a predictive maintenance (PdM) strategy. Yet, as per known industry standards, this type of information is latent in most cases, leading to significant (Stern, 2020).

As empirically known today, most performance metrics as well as condition parameters do correlate with the vehicle's usage pattern. State-of-the-art Internet of Things (IoT) platforms, including sensors and artificial intelligence (AI) software can be used to capture the operating condition of a fleet.

The challenge is to create a suitable Mining 4.0 Framework which supports data collection and analysis. Eventually the framework needs to provide sufficient visibility to identify underperforming assets, predict maintenance risks and suggest mitigating steps to improve fleet uptime.

CONDITION MONITORING IN FLEET OPERATIONS

Condition Monitoring (CM) is a key element of reducing downtime through the optimised scheduling of maintenance activities. Operational parameters and the usage of assets are monitored by an IoT platform, which acquires and analyses data. A decision-making system is used to optimise maintenance, offering a powerful tool to the management of mining operations.

Major mining equipment suppliers, including Caterpillar (Cat VIMS) and Komatsu (Komtrax Plus Monitoring) are already using telemetry systems to provide CM information locally (ie on board) and remotely (ie accessible from anywhere over the internet). Typically, a variety of embedded sensors are used to detect operational parameters, such as engine speed, location, speed of movement, engine oil pressure and fuel consumption rate. These combined with additional available information, such as service metre readings and number of operational hours per day, allow for an overall estimation of machines' health to be calculated (Caterpillar Inc., 2021).

ENABLING THE PREDICTIVE MAINTENANCE PARADIGM

PdM strikes a balance between reactive and preventive maintenance (Prometheus Group, 2022). Rather than running a vehicle to failure or replacing a part when it still has operational value, PdM allows organisations to conduct maintenance only when completely necessary.

IoT technology is progressing at an ever-increasing rate and several key factors are now accelerating the progress of AI. The cost point of advanced sensors is dropping rapidly, which when coupled with inexpensive computational capability allows large amounts of sensor data to be distilled into 'insights'. This in turn minimises the amount of data that needs to be transmitted, and importantly, allows for the display of computed data, trends and alarming locally.

Using encrypted wireless communication allows real-time monitoring, alarming and trending, without the expensive infrastructure costs associated with traditional site-wide control systems. The insights can then be displayed on one organisation-wide, IoT dashboard, that is platform agnostic and, with appropriate security protocols in place, can be integrated with Enterprise Resource Planning (ERP) software to schedule maintenance work orders, thereby closing the loop and enabling fleet operations to transition to a PdM paradigm.

MINING 4.0 FRAMEWORK FOR FLEET OPERATIONS

To enable the digital transformation of a mining fleet, the following five steps are recommended:

1. Establish a baseline – Digitalisation of a mining fleet should begin with an understanding of current asset capabilities, the desired future state, and the value to be created by increasing uptime. In addition, work order IT requirements should be mapped out and reporting requirements should be documented.
2. Define success criteria – The importance of tracking fleet maintenance metrics such as mean time between failures cannot be overstated. At the same time, financial (labour cost savings), environmental (emissions and waste reduction) and operational (productivity improvements) metrics cannot be ignored and need to be defined and monitored (Panik, 2023).
3. Manage data generation effectively – Most fleet operators face challenges with management of asset information throughout the asset life cycle, including data generation issues and documentation. An initial step towards the creation of a 'digital twin' should be the installation of 'smart sensors', to focus digitisation efforts on the areas of greatest value and impact (Jonas Friederich, 2022).
4. Convert data into insights – Most companies only use a fraction of the data they are already collecting, let alone the potential real-time volume that could be captured via IoT. Establishing the capability for an insight-driven organisation requires developing and embedding data science and analytic skills across the organisation.
5. Ensure that implementation involves all stakeholders – From executive leadership to maintenance personnel, different stakeholders may have completely different ideas about what objectives an IoT implementation must accomplish. Setting the right expectations upfront and having a crystal-clear plan, project rationale, and executive sponsorship, along with well-defined criteria for selecting a particular vendor, technology or approach is vital for a successful implementation. The more scientific the process that's utilised to manage the implementation, the higher the statistical probability of successful outcomes.

CONCLUSION

As we progress into a 'smarter fleet operation', a systematic approach is required to ensure good data, captured by intelligent sensors, resulting in practical outcomes and solutions driving the profitable mining operation. The prescribed strategy for achieving practical outcomes of Mining 4.0 initiatives and the suggested methodology and framework for realising value for the underperforming fleet operations will help in ushering in the transformation of these mines into more efficient operations.

REFERENCES

Caterpillar Inc., 2021, Jan 1. Why Condition Monitoring? Available from: <https://www.cat.com/en_US/support/maintenance/fleet-management/condition-monitoring.html>

Jonas Friederich, D P-M, 2022. A framework for data-driven digital twins of smart manufacturing systems, *Computers in Industry*, 10.

Panik, P, 2023, Nov 18. 15 Metrics Every Fleet Manager Should Be Tracking. Available from: <https://www.fleetio.com/blog/15-metrics-every-fleet-manager-should-be-tracking>

Prometheus Group, 2022, Oct 3. Reactive Vs. Preventive Vs. Predictive Maintenance. Available from: <https://www.prometheusgroup.com/resources/posts/reactive-vs-preventive-vs-predictive-maintenance>

Ravande, S, 2022, Feb 22. Unplanned Downtime Costs More Thank You Think. Available from: <https://www.forbes.com/sites/forbestechcouncil/2022/02/22/unplanned-downtime-costs-more-than-you-think/>

Stern, S, 2020, Jun 5. The future of maintenance for distributed fixed assets. Available from: <https://www.mckinsey.com/capabilities/operations/our-insights/the-future-of-maintenance-for-distributed-fixed-assets>

Unlocking value chain optimisation with a digital mining system

N Sarkar[1], T Vink[2], S Battersby[3], S Gulati[4] and L Okada[5]

1. Domain Owner, BHP, Brisbane Qld 4000. Email: nirman.sarkar@bhp.com
2. BOLT Product Manager, Deswik, Brisbane Qld 4000. Email: tao.vink@deswik.com
3. Lead Logistics, BHP, Brisbane Qld 4000. Email: scott.battersby1@bhp.com
4. Domain Owner, BHP, Brisbane Qld 4000. Email: sidharth.gulati@bhp.com
5. Marketing and Sales Manager, Deswik, Brisbane Qld 4000. Email: louis.okada@deswik.com

INTRODUCTION

This paper examines a successful project implemented by BHP Mitsubishi Alliance (BMA) and the Polymathian team at Deswik, aimed at enhancing short-term scheduling processes to reduce vessel turn times in the BMA Central Queensland coal value chain. The project's objective was to digitalise the planning process to enable planners to make data-driven insights to improve the profitability of the value chain. The strategy involved developing a digital mining system that incorporates data storage, cloud computing, and the ability to meet the integration needs of both internal and external business systems. This was complemented by a sophisticated, optimisation-based, decision-support tool to enhance the planning teams' ability to make timely and effective decisions.

The integration of this custom-built digital mining system with a commercially available optimisation tool, BOLT, culminated in a state-of-the-art, digitised, automated, and optimised planning platform. This platform has driven significant cost savings in vessel demurrage and enhanced the value chain's overall profitability.

MANAGING A COMPLEX VALUE CHAIN

BHP Mitsubishi Alliance (BMA) operates a network of four coalmines in the Bowen Basin, exporting through the BMA-owned and operated Hay Point terminal. BMA can also use the other third-party ports in the region. Every day, BMA's logistics planners plan material movements across its complex multi-mine, rail, port, and sea-borne value chain.

To maximise value from the operation, they aim to supply the best product on time and to their customer's needs. Creating plans that deliver product on-specification and on time requires accurate data for both the current state of the system and for all planned future activities.

Breakdowns in communication, data flow and data accuracy across the value chain, between planners, operations and marketing can result in defective plans, potentially impacting mine operations or incurring penalties and demurrage costs in the millions of dollars per annum.

The original planning process

BMA's weekly short-range forecasting process has always been complex, right from assimilating data to meeting demand at port while adhering to physical constraints. At the time of the project execution BMA had six mine sites. Each of these mines were developed at different times and with different priorities, resulting in varying levels of technological maturity, systems, and processes. Multiple versions of truth among these systems add to the complexity. A seemingly trivial task of gathering opening inventories across 12 products from five mine sites could be time intensive as it involves fetching data from different systems, emails, chats, and phone calls. Similarly, procuring the most recent plan/schedule and capacity data from individual parts of the supply chain, including five CHPPs, three train service providers, two ports, and vessels, was often time-consuming.

Plans were constructed by manually matching demand derived from vessel schedules with the available supply using a macro-based Excel spreadsheet. The spreadsheet produced inventory forecasts by product and location based on current inventory, planned production, planned train movements and vessel schedules. Available capacities for trains, rail network, port infrastructure and vessels were manually assigned and iteratively adjusted to reach a suitable compromise. For example, trains were manually assigned to each combination of train load out (TLO), product and calendar date by going through each cell in the input matrix. This time-consuming process was necessary to produce a feasible solution. However, any form of optimisation was practically impossible.

To make matters worse, several disruptions, such as weather delays, unplanned equipment downtimes, and out-of-spec products, could quickly make these plans obsolete, and the entire process must be repeated in a much shorter timeline. This results in high demurrage costs and missed opportunities from the standpoint of product optionality. Only a handful of individuals with intricate knowledge of BMA's supply chain can manage this process, posing significant business continuity challenges.

BUILDING A DIGITAL MINING SYSTEM

Due to the difficulty and time-intensive process of planning such a complex value chain, BMA identified the need for a more sophisticated planning platform capable of optimising operations from mine to market.

To support the needs of the team to make these data-driven decisions, a digital mining system was designed as the data backbone to digitalise and facilitate the automation of data workflows. The goals of the system are listed below.

- Act as the central source of truth for mining data for the BMA's supply chain management team.
- Manage and automate the planning process required to operate the logistics and port/shipping operations.
- Standardise the data interface with internal and third-party software systems.
- Securely manage the handling of data with a robust authentication and authorisation model.

Standardising the data

The digital mining system is responsible for collating the various data sources from disparate systems, each with their own file formats, naming conventions, data refresh rates and access rules. For example, to access stock inventory levels across the value chain, data is pulled from multiple locations across different mine sites. Some sites provide updates every shift (shift timings can be different across sites), few others provide hourly updates, and the rest of the sites provide near real time updates.

Having a trustable and timely source of data where point-in-time estimates of inventory is critical to decision-making. Calibration errors can accumulate over time and are manually corrected periodically. For instance, during system downtimes, the tonnes calculated based on planned production rates are used instead of measured estimates. Additionally, a small but significant amount of product in transit through the rail network must be accounted for. The team developed and standardised a set of business rules to determine the most appropriate source of information for each scenario. Various stakeholder groups validated and approved these rules to ensure a consistent and agreed-upon version of the truth. A similar approach was used to standardise rail and port movement data.

Automation and data integrations

A central component of the digital mining system is its ability to facilitate seamless data exchange through flexible APIs. This design enables the system to manage data access via a centralised end point, which simplifies interactions with various external systems. This centralised management is particularly beneficial for integration with decision-support systems like BOLT, which rely on multiple data sources.

Another crucial feature of the system is the automation of managing the data pipeline. This automation ensures that the system continuously retrieves the most recent data sets from a variety of sources. This capability streamlines the flow of information and supports a more dynamic and responsive planning environment.

Data input mechanism: Automated data pipelines sanitise and standardise data from 6 source systems and make it available for the optimiser (BOLT) once a day. A data health report with details of each source systems is also provided to end users to keep them aware of any system failure and potential stale data.

Data processing: Users can import the most recent data from the optimiser into a scenario with the click of a button. The imported data is reviewed through charts and tables. Required changes are made for the particular scenario, and the optimisation engine is triggered. The optimisation results are available within a few minutes.

Optimisation results: Results for a scenario is available to be assessed through various reports and dashboards. Based on the output, users can make further changes iteratively to the input data until a satisfactory solution is achieved. At this stage the scenario can be published when all input and output data is pushed back into the database for wider visibility of the scenario using tools such as power BI. Figure 1 shows the high-level data flow between the two environments.

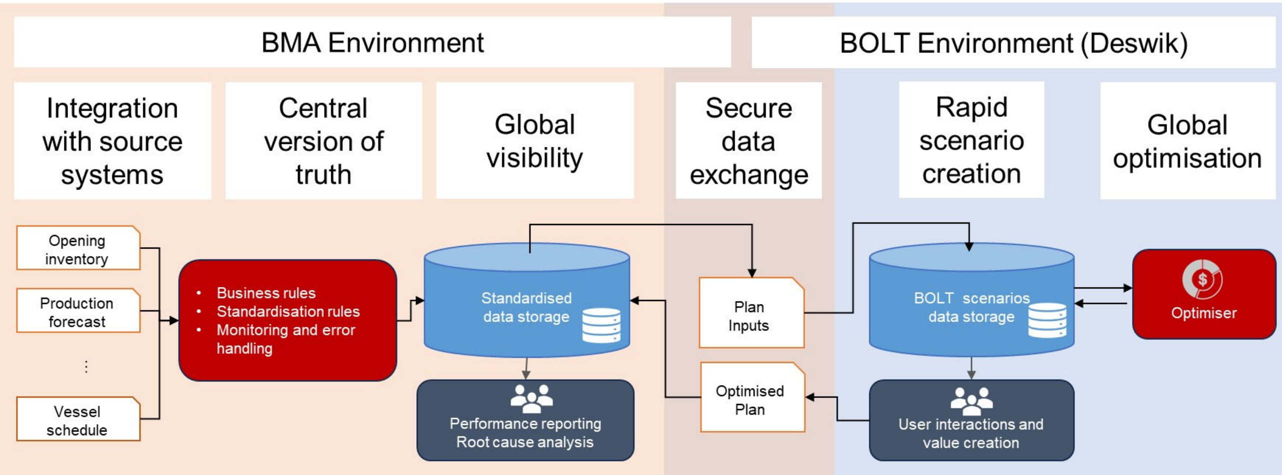


FIG 1 – Data integrations diagram.

Technical architecture design considerations: Several factors were considered when deciding on the integration approach between BMA and Polymathian. The integration needed to be/have:

- Quick to configure.
- Minimal security risk, not reaching into each other's systems.
- Low cost, very high uptime, redundancy.
- Ability to trigger actions (eg new data is ready for processing).
- Ability for user to get older data if required.
- Automatic data retention polices.

MAKING DECISIONS WITH INDUSTRIAL MATHEMATICS

BMA recognised that the existing process of scheduling the coal value chain was sub-optimal due to its vast scale and complexity. They decided that a computer-assisted approach was necessary and partnered with Polymathian, experts in the application of Industrial Mathematics software to answer tough industry planning and scheduling problems. They chose BOLT, a commercial off-the-shelf tool that uses Mixed Integer Linear Programming (MILP) techniques, a form of Mathematical Optimisation, to optimise the logistics and marketing plans for the entire BMA coal system. Figure 2 highlights the components of Industrial Mathematics.

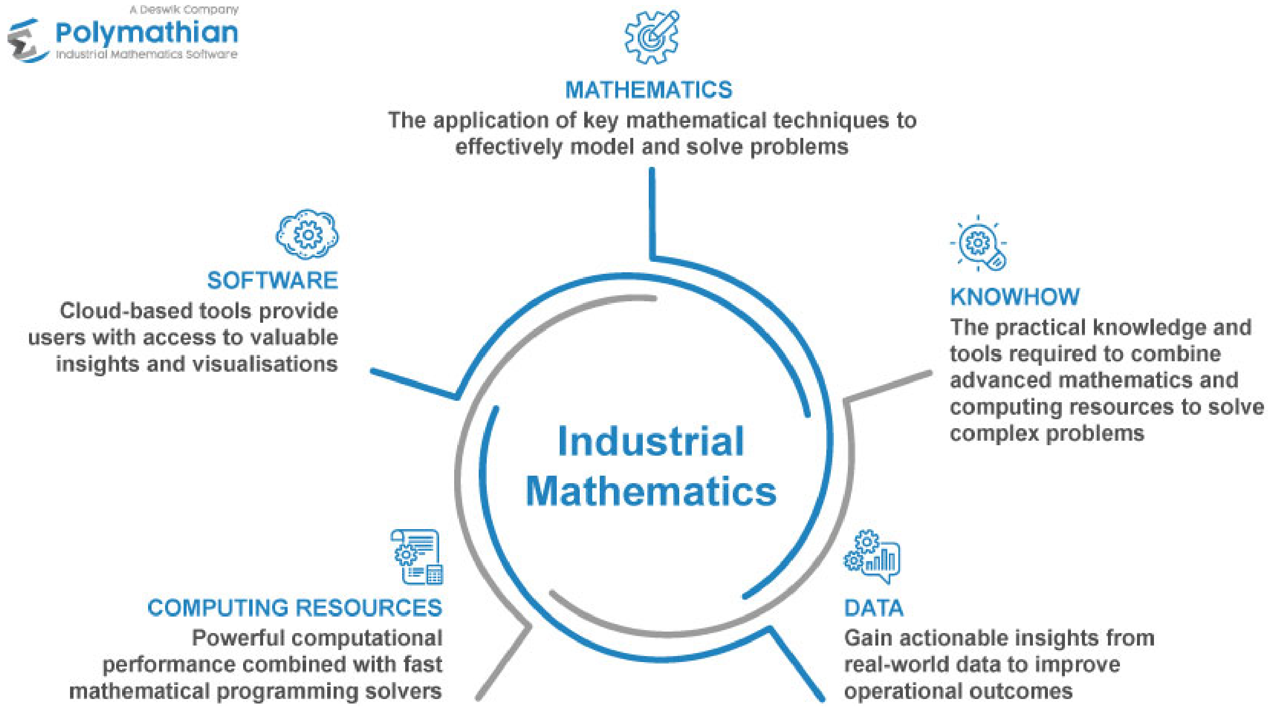


FIG 2 – What is industrial mathematics?

What is mathematical optimisation?

Mathematical optimisation (MO) is a powerful prescriptive analytics technique that enables companies to solve large and complex business problems. According to Gurobi Optimization (2022), 85 per cent of Fortune 500 companies use MO in their daily operations to make better business decisions, which results in billions of dollars saved annually.

Within the field of MO, Polymathian utilise a technique known as linear programming to build mathematical models of the customer's problems. This model can then be solved to yield provably optimal solutions to the original problem. The ability to identify the quality and how close to optimality a particular solution is, determines the key attribute of linear programming and why it is so widely used.

Scenarios are modelled to include business goals (objectives), decisions (variables) and rules (constraints) (Figure 3). Together, these three elements comprise a standalone model which can be solved to maximise or minimise the goal. This process can return a single solution, or a range of solutions which achieve the goal in different ways. By running multiple scenarios, users can gain valuable insights into how the optimal solution changes with respect to the planning rules and decisions.

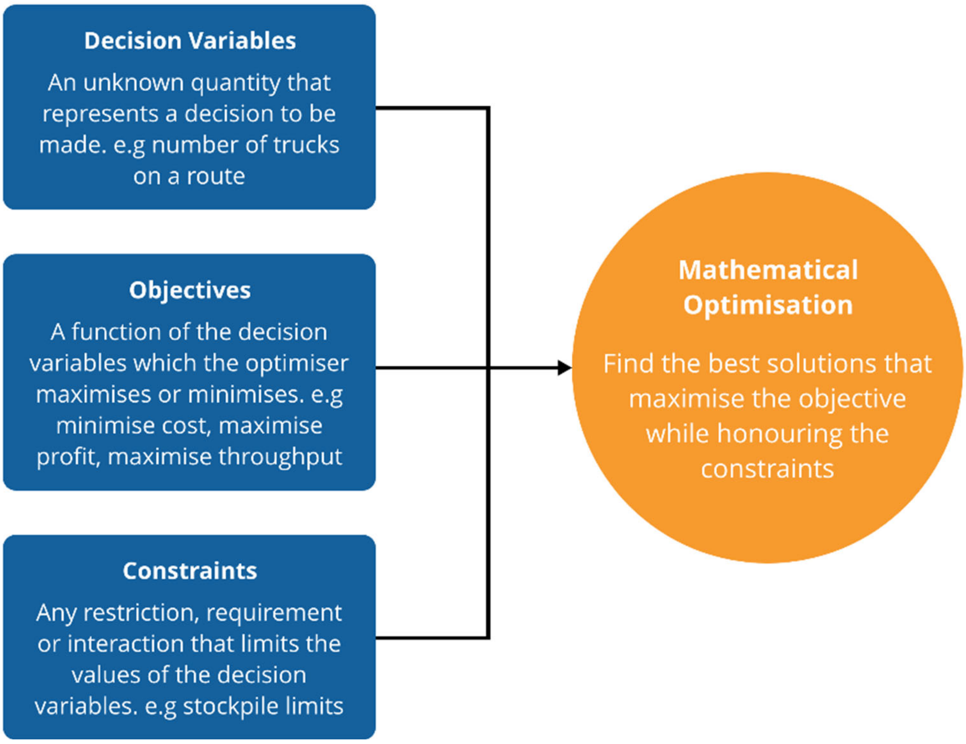


FIG 3 – What is mathematical optimisation?

How does bolt solve the value chain problem?

BMA selected BOLT because it can consider the entire value chain and look forward to the full planning horizon to ensure the best decisions are made. BOLT is a webapp for users to manage scenarios, update and modify data, run, and review optimisations. Figure 4 shows a step from the BOLT webapp where a network is visualised.

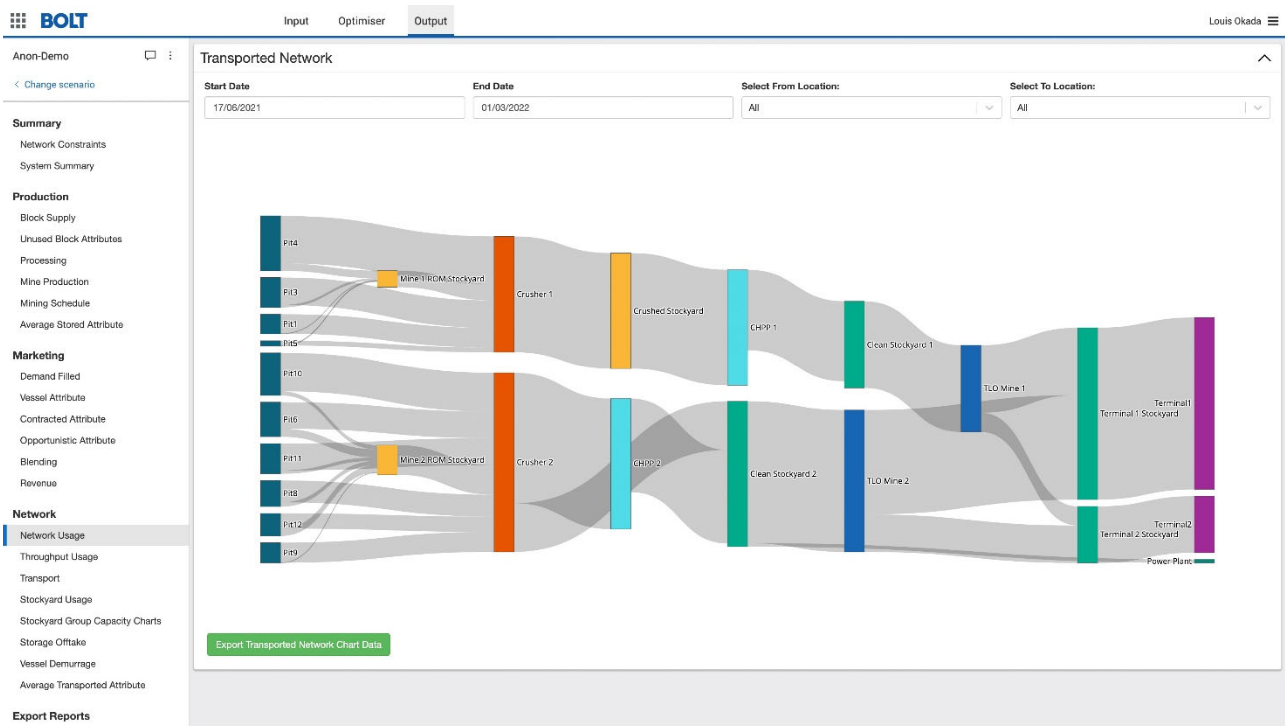


FIG 4 – An example BOLT interface.

BOLT uses a multi-commodity network-flow optimisation formulation to model material moving though a capacity-constrained system. A network-flow model finds the minimal-cost flow through a network, where a network consists of a set of nodes and a set of arcs connecting the nodes. The multi-commodity network-flow extends this by capacitating multiple commodities across the set of arcs.

An example of the basic multi-commodity network-flow is defined below (Ahuja, Magnanti and Orlin, 1993):

- $G(V, E)$ is a network flow graph with V defining the vertices and E defining the edges, where E is a set of pairs of vertices.
- $(u, v) \in E$ define the edges with capacity $c(u, v)$.
- There are k commodities $K_1, K_2, \ldots, K_k$ where $K_i = (s_i, t_i, d_i)$ given s_i is the source vertex of commodity i and d_i is its demand quantity, and t_i is the sink vertex of commodity i.
- $f_i(u, v)$ is a variable defining the fraction of flow i along the edge (u, v), where $f_i(u, v) \in [0,1]$ allowing flow to be split across multiple edges.

The assignment of all flow variables must satisfy the following constraints.

(1) Link capacity: The sum of all flows routed over a link does not exceed its capacity.

$$\forall (u, v) \in E: \sum_{i=1}^{k} f_i(u, v) \cdot d_i \le c(u, v)$$

(2) Flow conservation on transit nodes: The amount of a flow entering an intermediate node is the same that exits the node.

$$\forall i \in \{1, \ldots, k\}: \sum_{w \in V} f_i(u, w) - \sum_{w \in V} f_i(w, u) = 0 \text{ when } u \neq s_i, t_i$$

(3) Flow conservation at the source: A flow must exit its source node completely.

$$\forall i \in \{1, \ldots, k\}: \sum_{w \in V} f_i(s_i, w) = 1$$

(4) Flow conservation at the destination: A flow must enter its sink node completely.

$$\forall i \in \{1, \ldots, k\}: \sum_{w \in V} f_i(w, t_i) = 1$$

The objective is to minimise the total cost given $a_i(u, v) \cdot f_i(u, v)$ is the cost for sending flow of commodity i on edge (u, v).

Minimise:

$$\sum_{(u,v) \in E} \sum_{i=1}^{k} a_i(u, v) \cdot f_i(u, v) \cdot d_i$$

Polymathian have extensively extended this base formulation concept allowing modelling of concepts including time, stockpiling, blending, transformation, and vehicles.

To align with the goal of reducing vessel turn time the objective was set to minimise total variable cost, largely made up of demurrage.

The decisions that are made in each time period include:

- How many trains to send from each train load point to each port.
- What product to place on each train.
- What sequence to load vessels.
- What berth each vessel should be loaded.
- What stock levels to hold of each product.

The constraints that are considered include:

- Product production at each mine.
- Rail schedules, capacity limits and contracts.
- Port in-load and out-load rates.
- Vessel arrival time.
- Mine stock level targets and limits.
- Port sock level target and limits.

BOLT takes the input data and formulates a mathematical optimisation, that is, a set of equations provided to a commercial optimisation engine. On-demand computing is started in the cloud, and the problem is solved by focusing on optimising the objective. The solution is then available in the BOLT webapp for review.

PLANNING IN PRACTICE

Since implementing the mining system and BOLT, the workflow that planners now use has been simplified significantly; they:

- create a new scenario in BOLT with the appropriate planning period
- click to import the latest data from BMA's digital mining system
- review the input data via charts and tables
- optimise and review the plan using charts and tables
- potentially run other what-if scenarios by varying the inputs
- publish the preferred scenario back to the BMA digital mining system.

This process can be completed within an hour, allowing planners additional time to be spent running further what-if scenarios or analysing the value chain.

This has been a great benefit to the planners as they are often asked 'what-if' questions by others. For example, one of the mines asked if washing a different product for the next three days was possible. The planning team were able to quickly run a new scenario in BOLT by simply changing the product demand profile and comparing it with the baseline scenario of washing to the original product specification. After analysing the difference in overall profit margins, it was identified that there would be a loss of $400k due to how it would affect downstream activity in the supply chain. Previously, this was a very difficult question to answer, but now the planners have a quick way to run a what-if analysis and provide a mathematically and financially driven answer. Ultimately, the combination of a digital mining system and industrial mathematics ensured the correct decision was made.

Other questions that can be answered include:

- Given some options, what product should be put on a vessel?
- What will be the impact of different maintenance options?
- Could more vessels be added?

Accurate and up-to-date input data combined with a quick turnaround in scenario creation and optimisation allow the planners to confidently answer these questions.

CONCLUSION

This project has demonstrated that improved decision-making processes can unlock a substantial amount of additional value. Improvements to the robustness of planning data have made the entire process more reliable, especially during disruptions.

Looking ahead, the next steps for this initiative involve refining the planning process to address daily and shift-level challenges and expanding the scope to include monthly and yearly planning that aligns with the business's strategic objectives. Additionally, there is a focus on enhancing the granularity of optimisation, such as incorporating the mine product specifications in the model.

The future potential of this system lies in its ability to serve as a comprehensive integrated planning platform—a single pane of glass—that supports and manages logistics, port, and marketing operations. This will not only streamline operations but also significantly boost productivity and profitability across the board.

REFERENCES

Ahuja, R K, Magnanti, T L and Orlin, J B, 1993. *Network Flows – Theory, Algorithms, and Applications* (Prentice Hall).

Gurobi Optimization, 2022. Gurobi Helps Software Companies Successfully Integrate Optimization Into Their Solutions [online]. Available from: <https://www.gurobi.com/news/gurobi-helps-software-companies-successfully-integrate-optimization-into-their-solutions/> [Accessed: 9 April 2024].

Structural analysis and modelling in an evolving mineral resources operation

S Shahin[1], A Jani[2] and N Arrys[3]

1. Specialist Structural Geologist, Rio Tinto Iron Ore, Perth WA 6000.
   Email: sam.shahin@riotinto.com
2. Specialist Structural Geologist Tinto Iron Ore, Perth WA 6000. Email: akash.jani@riotinto.com
3. Specialist Geotechnical Engineer, Rio Tinto Iron Ore, Perth WA 6000.
   Email: nanang.arrys@riotinto.com

INTRODUCTION

Optimising pit slope stability and reducing strip ratio of a mining operation are two key tasks in geotechnical engineering. With a growing demand for minerals and an increasing cost associated with extraction, companies are constantly re-evaluating the viability of mineral deposits and challenging their geological understanding.

Within Rio Tinto Iron Ore (RTIO), the Structural Geology (SG) team investigate and collect critical data, such as point based orientations, mapping and geological inferences from adjacent pits to re-model deposits where previous interpretations have failed to account for structurally controlled slope failures.

This work outlines the key methods utilised by the Structural Geology team which form the foundations of informed orebody knowledge and subsequent geotechnical design recommendations. This publication utilises the results from a recent analysis to highlight the benefits of this methodology and how it has impacted the economics of an operation through optimisation of a pit wall 'cutback' and crest relocation.

PRIMARY DATA COLLECTION AND INHERENT BIAS

Committing to a resource grid drill campaign of vertical holes as the primary source of data collection is commonplace in bulk commodities such as iron ore. Although this is an effective way of proving a resource estimate, it often bias's data collection to a specific orientation and significantly reduces the capability to identify and qualify structural complexity. This is especially true in the context of the Hamersley Basins, Marra Mamba Iron formation, a ~2.7 Ga sedimentary deposit consisting of banded iron formations (BIF) and shale units (Trendall *et al*, 2004). These rocks have preserved and endured multiple deformation events on an orogenic scale resulting in complex fold systems and structures (Tyler and Thorne, 1990).

Consequently, these limitations and biases make it difficult to construct a realistic and coherent structural model that identifies adverse structural domains. Without the consideration of complexity and the capability of capturing these structural domains, mining operations run the risk of inadequately designed pit-slopes that may fail and potentially harm people.

STRUCTURAL DATA COLLECTION

Structural Geologists at Rio Tinto Iron Ore are responsible for mapping mined batter faces as they are uncovered for the purpose of model reconciliation. The reconciliation process is a key part in identifying whether current interpretations are still relevant and fit for purpose.

Some open cut pits in the RTIO portfolio have operational life expectancies of several decades. With this comes the challenge of collecting data at a bench scale resolution for the entirety of the pit's life. Utilising drone imagery and photogrammetry scanning methods we can produce 3D georeferenced reality models of pits requiring analysis (Thiele *et al*, 2017). This has the benefit of providing a holistic view of the overall pit slope while maintaining the capability to acquire bench scale resolution mapping data (Dey, Roy and Matin, 2021). Furthermore, these scans provide data collection opportunities in geotechnical sensitive areas that pose potential safety risks to personnel. More specifically, these methods can provide data collection opportunities on failure surfaces (Read and Stacey, 2019) within the pit slope. Measurements and understanding of these failure surfaces are integral to identifying the root cause of the failures and where the design assumptions and geological model have failed to account for said adversity.

REGIONAL-LOCAL SYNTHESIS

In addition to pit mapping Structural Geology leverages an understanding of regional tectonic process and structures that reflect specific deformational phases. Fold patterns and fold corridors that define the bedding fabric of these sedimentary deposits can be attributed to the orientation of the orogenic processes that formed. them and more importantly can dictate if a geotechnical design domain is rock mass controlled or structurally controlled in relation to the pit design.

By understanding the regional terrains and structures, Structural Geology can link smaller scale structural features present within a pit environment to the regional scale structures. This practice is especially effective in the context of parasitically folded domains where identification of fold vergence can provide contextual and spatial information in data poor areas. Holistically, this provides confidence in interpretation and reduces uncertainty in the continuation of structures through the modelled area.

The intersection between the geological bedding fabric and the strike of the pit can determine if a geotechnical design domain is rock mass controlled or structurally controlled. Hence the importance of identifying and understanding the fold domains present within the orebody and the subsequent design methodology utilised to calculate the recommended slope design parameters in the case of rock mass controlled or structurally controlled domains.

A culmination of data and informed interpretations go on to produce a 3D geological model. For the representative case highlighted in the results, this took the form of a changed interpretation of the orebodies fold style. Previous modelling of the orebody appeared to represent an east–west striking, upright and open syncline. Structural Geology produced a new interpretation, consisting of an east–west striking, upright and open syncline that has experienced refolding due to NE-SW shortening. The introduction of a NW-SE striking fold corridor to the interpretation and subsequent model has proven to reconcile with mapping data to a higher level than the previous interpretation and model. Furthermore, the historic failures in the pit slope can be accounted for as this fundamental change in the interpretation accounts for previous spatial non-conformance of the shale units the failures occurred along.

RESULTS AND CONCLUSION

Utilising 2D limit equilibrium analysis on critical geotechnical sections, optimisation of inter-ramp angle and batter face angle for the proposed cutback design was achieved. A four degree change (29° to 33°) in the inter-ramp as proposed by ultimate design US827 would have an estimated volumetric saving of ~$4.28*10^6$ m^3 of material handling across 1 km of wall. This volumetric saving estimate can translate to a cost saving difference of ~$250M in waste rehandling and further unlocks 60 Mt of high-grade ore.

Table 1 summarise the optimisation potential of the overall slope angle (OSA) along a single critical section based on the recent analysis. The factor of safety (FoS) was achieved while optimising the OSA by up to five degrees in domains represented by cross-section (XS) 03 in the current design US727.

The principal contributions of this methodology include improved mine economy, reduction in mining footprint and carbon emissions and implementation of confident pit designs.

Pioneered by the Structural Geology team, Rio Tinto’s West Pilbara operations are increasingly adopting these techniques for new and historic deposits. The uptake and increase in UAV style data collection has also become standard across both East and West operations with the realisation of its superiority and versatility in surveying and data collection.

Next steps include expansion and adoption of a complete workflow based on this study’s findings, automation of photogrammetry surveys and automation of data extraction from surveys.

TABLE 1

Overall Slope Angle and Factor of Safety comparisons for differing pit scenarios and/or stages.

Section lines	Scenario/ pit stage	Slope height	Current geometry (OSA)	Achieved FoS	Optimised geometry (OSA)	Optimised FoS	Target FoS
XS03	As-built	144m	38°	**1.44**	n/a	**n/a**	1.2
	US727	147m (IR-upper)	29°	**1.35**	34°	**1.31**	1.3
		41m (IR-lower)	34°	**2.28**	34°	**2.32**	1.3
	US827	180m	29°	**1.30**	33°	**1.28**	1.2

REFERENCES

Dey, J, Roy, S and Matin, A, 2021. Drone photogrammetry: a structural data gathering tool for open pit mining geotechnics, in *SSIM 2021: Second International Slope Stability in Mining* (ed: P M Dight), pp 135–148 (Australian Centre for Geomechanics: Perth). https://doi.org/10.36487/ACG_repo/2135_06

Read, J and Stacey, P, 2009. *Guidelines for Open Pit Slope Design*, CSIRO Publishing.

Thiele, S T, Grose, L, Samsu, A, Micklethwaite, S, Vollgger, S A and Cruden, A R, 2017. Rapid, semi-automatic fracture and contact mapping for point clouds, images and geophysical data, *Solid Earth*, 8(6):1241–1253. https://doi.org/10.5194/se-8-1241-2017

Trendall, A F, Compston, W, Nelson, D R, De Laeter, J R, and Bennett, V C, 2004. SHRIMP zircon ages constraining the depositional chronology of the Hamersley Group, Western Australia, *Australian Journal of Earth Sciences*, 51(5):621–644. https://doi.org/10.1111/j.1400-0952.2004.01082.x

Tyler, I M and Thorne, A M, 1990. The northern margin of the Capricorn Orogen, Western Australia—an example of an Early Proterozoic collision zone, *Journal of Structural Geology*, 12(5–6):685–701. https://doi.org/10.1016/0191-8141(90)90082-a

A new insight into standardisation of Mine IoT

A Shirbazo[1], B Li[2], S Saydam[3], S Ata[4] and H L Ramandi[5]

1. PhD Student, UNSW, Sydney NSW 2052. Email: a.shirbazo@unsw.edu.au
2. Associate Professor, UNSW, Sydney NSW 2052. Email: binghao.li@unsw.edu.au
3. Professor, UNSW, Sydney NSW 2052. Email: s.saydam@unsw.edu.au
4. Associate Professor, UNSW, Sydney NSW 2052. Email: s.ata@unsw.edu.au
5. Senior Lecturer, UNSW, Sydney NSW 2052. Email: h.lameiramandi@unsw.edu.au

ABSTRACT

The integration of internet technology into industrial sectors has significantly accelerated the adoption of Internet of Things (IoT) devices, transforming communication, data aggregation, and information distribution. The mining industry has embraced this evolution by deploying IoT devices and advanced technologies like autonomous robots and sensors to enhance operational safety. These sensors enable real-time data transmission and continuous monitoring of key parameters, providing decision-makers with timely insights. However, the interconnected nature of these devices has introduced complexities, resulting in inconsistencies across operations. Addressing these challenges, this research explores the application of modern digital principles to the mining industry through the Reference Architecture Model Industry 4.0 (RAMI 4.0). RAMI 4.0 offers a robust framework that integrates digital and physical systems, promoting data transparency, interoperability, and decentralised decision-making. This study aims to briefly introduced framework designed for the unique challenges of mining operations, leveraging the latest digital technologies. The lack of standardisation in the mining sector highlights the need for a comprehensive approach to tackle issues such as interoperability, scalability, security, safety, and repeatability. Establishing standard procedures can ensure smooth interaction between connected devices, ultimately enhancing operational efficiency in the growing IoT ecosystem within the mining industry. Introducing a well-defined reference architecture like RAMI 4.0 can streamline management processes and improve operational efficiency in mining. By adopting this framework, the mining industry can effectively navigate the challenges of digital transformation, leading to a more connected and resilient future. The study concludes that RAMI 4.0, with its structured approach, can significantly enhance the efficiency and productivity of mineral processing operations, fostering sustainable growth in a digitally driven industrial landscape.

INTRODUCTION

The integration of the internet into industrial sectors has catalysed the widespread adoption of Internet of Things (IoT) devices, revolutionising communication, data aggregation, and information dissemination processes. Notably, the mining industry has embraced this technological evolution, deploying IoT devices and leveraging cutting-edge technologies such as autonomous robots and advanced sensors to enhance safety measures across various mining operations.

The deployment of advanced sensors has enabled real-time data transmission, facilitating continuous monitoring of critical operational parameters and empowering decision-makers with timely insights. However, the interconnected nature of devices within the mining ecosystem has introduced complexities, leading to a noticeable lack of consistency across operations.

RAMI 4.0 serves as a robust structure that aligns with the core tenets of Industry 4.0, emphasising the seamless integration of digital and physical systems, data transparency, interoperability, and decentralised decision-making. By contextualising smart manufacturing within the mining sector, this study aims to establish a comprehensive framework tailored to the industry's unique operational demands while harnessing the transformative potential of digital technologies.

The absence of standardisation within the mining sector underscores the need for a comprehensive approach to address interoperability, scalability, security, safety, and repeatability concerns. The envisioned standardisation process aims to promote seamless interaction between interconnected devices, ultimately improving operational efficiencies within the mining industry's evolving IoT ecosystem.

It is essential to recognise that the introduction of a well-defined reference architecture holds the potential to streamline management processes and enhance operational efficiencies within the mining sector. By embracing the principles of smart manufacturing and adopting a tailored framework like RAMI 4.0, the mining industry can navigate the complexities of digital transformation with confidence and agility, paving the way for a more connected and resilient future.

RAMI 4.0

The delivered IIoT system aligns with industry standards, particularly the RAMI 4.0, ensuring robust data collection for production operators (Waters *et al*, 2022). RAMI 4.0 is a widely used model in Industry 4.0 applications, providing a framework for organising complex connections and functions. It consists of standard frameworks and guidelines applicable to any Industry 4.0 asset, with IIoT-specific RAs developed to address implementation challenges (Alexopoulos *et al*, 2018). The adoption of standards and RAs is crucial for promoting interoperability within Smart Factories, facilitating the description of components, systems, processes, and interactions (Grangel-González *et al*, 2017). A suitable RA will assist industrialists in comprehending the implications of smart manufacturing for their operations, such as enhanced flexibility and control. RAMI 4.0 was adopted by the IEC as a Publicly Available Specification (PAS) for Smart Manufacturing (IEC PAS 63088:2017).

MINERAL PROCESSING IN INDUSTRY 4.0

The value chain within the mining sector is depicted in Figure 1. As you can observe, it typically consists of five distinct stages: exploration, development, mining, processing, and delivery to market. For the sake of standardisation, it's necessary to choose one of these segments. Mineral Processing appears to be a highly suitable candidate within this segment. This is because Mineral Processing involves a diverse array of tools and scenario-based procedures that can effectively integrate with RAMI 4.0. This selection underscores the critical role of mineral processing within the broader mining life cycle, highlighting its significance in the overall operational process.

FIG 1 – Value chain of mining industry.

The mineral processing steps are delineated in Figure 2, showcasing the multifaceted tasks and processes integral to this segment. From ore extraction to the refinement of valuable minerals, each step demands meticulous attention to detail and specialised expertise. To streamline our approach and ensure optimal alignment with RAMI 4.0. By focusing on the core technical aspects, we can enhance the effectiveness of our integration efforts and maximise the benefits of adopting RAMI 4.0 within the mineral processing segment. This refined focus will enable us to harness the full potential of smart manufacturing principles and technologies in optimising mineral processing operations.

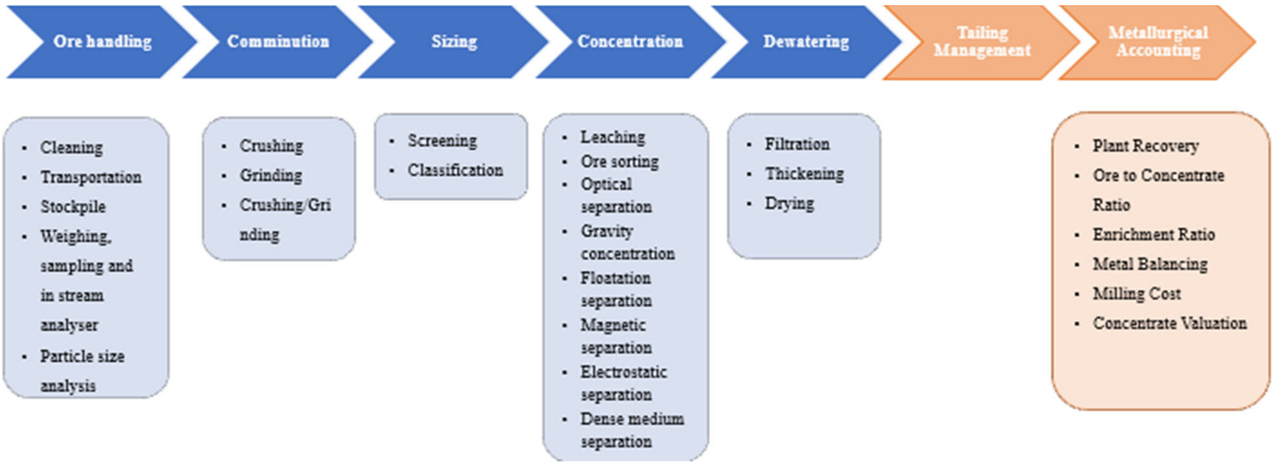


FIG 2 – Mineral processing stages.

CONCLUSION

In conclusion, this study has endeavoured to introduce the transformative concept of smart manufacturing and highlight the utility of the RAMI 4.0 framework for standardisation within diverse industrial contexts. In fact, RAMI 4.0 is selected as an appropriate tool for standardisation purposes. Through a focus on mineral processing in the mining value chain, we have underscored the importance of leveraging innovative approaches to enhance efficiency and productivity. Moving forward, the development of detailed industrial scenarios and the identification of smart devices will be crucial steps in realising the potential of smart manufacturing in revolutionising mineral processing and, by extension, the broader mining industry.

REFERENCES

Alexopoulos, K, Koukas, S, Boli, N and Mourtzis, D, 2018. Architecture and development of an Industrial Internet of Things framework for realizing services in Industrial Product Service Systems, in *Procedia CIRP*, Elsevier, B V:880–885. https://doi.org/10.1016/j.procir.2018.03.152

Grangel-González, I, Baptista, P, Halilaj, L, Lohmann, S, Vidal, M-E, Mader, C and Auer, S, 2017. The Industry 4.0 Standards Landscape from a Semantic Integration Perspective, in 22nd IEEE International Conference on Emerging Technologies and Factory Automation, Cyprus.

IEC PAS 63088:2017, 2017. Smart manufacturing – Reference architecture model industry 4.0 (RAMI4.0).

Waters, M, Waszczuk, P, Ayre, R, Dreze, A, McGlinchey, D, Alkali, B and Morison, G, 2022. Open Source IIoT Solution for Gas Waste Monitoring in Smart Factory, Sensors 22. https://doi.org/10.3390/s22082972

Can robots break the drill and blast bottleneck in underground roadway development in hard rock?

N A Sifferlinger[1], M Berner[2] and E Fimbinger[3]

1. Professor, Montanuniversitaet Leoben, Leoben 8700, Austria.
   Email: nikolaus-august.sifferlinger@unileoben.ac.at
2. Senior Scientist, Montanuniversitaet Leoben, Leoben 8700, Austria.
   Email: michael.berner@unileoben.ac.at
3. Senior Scientist, Montanuniversitaet Leoben, Leoben 8700, Austria.
   Email: eric.fimbinger@unileoben.ac.at

ABSTRACT

Today, the advance rate of underground roadway development by drill and blast operation is limited by the need to ventilate the toxic blast fumes after each cycle. In deep mines this usually is only possible during shift changes when the related mine sections are free of persons.

This results in roadway development advance rates of 4 m per shift, or 12 m per day. For long roadways this is a limiting factor in mining development in deep mines.

Companies like EPIROC, KOMATSU, ROBBINS and SANDVIK are making serious R&D efforts to disc-cutting mobile miners to overcome this bottleneck. However, today, the achieved advance rates are less than 12 m per day in hard rock.

If we achieve full robotisation and/or teleoperation from a safe place for drill and blast operation of an underground roadway development section, we could eliminate this bottleneck.

Poisonous blasting fumes do not affect robots and machines as long as these fumes do not create aggressive acids.

If we can keep the blast fumes isolated in the roadway development section for the shift until the next ventilation opportunity (eg shift change or designated ventilation times), we can do the drill and blast cycle more often in a shift, which will significantly speed up the advance rate.

This requires robotisation of all work steps in the section: surveying, drilling, charging of explosives, blasting, loading and transporting material, roof support, installation of infrastructure etc. Also, cache storage for the material is needed.

Special care for the ventilation system to keep the blasting fumes under control in the section is necessary.

The paper discusses the aspects needed to achieve this robotisation and the related technical and operational tasks.

INTRODUCTION

Today, the daily advance rate in roadway development in underground mining in hard rock conditions (uniaxial compressive strength: UCS > 160 MPa and high abrasive) in drill and blast operation is limited. The ventilation of the toxic blast fumes (see Figure 1) can only be done when the ventilation way is free of persons. In deep mines this is usually only possible during shift change or extra evacuation. Therefore, under good conditions in a three shift-cycle, it is only possible to initiate up to three blasts. If the length of one blast is 4 m a maximum of 12 m can be achieved per day.

FIG 1 – Blast fumes in a roadway. Nitrogen oxides are visible as yellow/brown colour (image courtesy of Euromines).

To overcome this bottle neck of drill and blast operation in roadway development the introduction of mechanical cutting systems with disc tools in part face operation is underway by several OEMs over the last years. So far none of these systems has achieved more than 10 m of daily advance rate in hard rock and more research and development is necessary (Sifferlinger, 2023).

Full face tunnel boring machines can achieve 25 m advance and more per day in hard rock. But in case of a longer stop in deep mining they are in danger of being squeezed in and caught by rock mass subsidence (Narimani Dehnavi, 2024), which needs than manual actions to free them again. The big turn radius of at least 60 m and the need to fit a floor in the circular profile does not help in mining either.

If a system is created, by which humans in the roadway development section are replaced by teleoperation and robotisation and the blasting fumes can be kept in the affected section until the next opportunity to ventilate, more than one blasting cycle can be done in one shift.

For robots the toxic blast fumes are not a problem as long as corrosion effects are low.

With such a system the advance rate in roadway development in underground mining can be at least doubled.

CONCEPT

Figure 2 shows a first concept how a robotised roadway development in a 5 × 5 m profile section could look like.

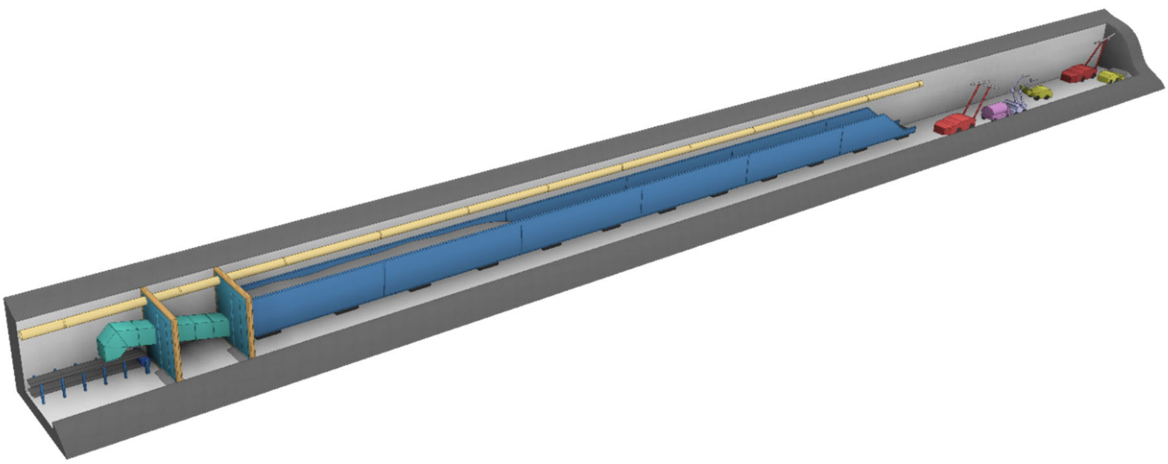


FIG 2 – concept drawing of a robotised, teleoperated roadway development section with drill jumbo, LHDs, explosive charger and roof support unit. A mobile storage system for the material blasted before and a mobile ventilation air lock system needs to keep the blast fumes in the section until the next ventilation opportunity (drawing courtesy of E Fimbinger).

In a 5 × 5 m profile section with a blasting pull of 4 m each blasting takes out about 100 m^3 of material. With a loosening factor of two there are about 200 m^3 of material which needs to be removed after each blast.

A designated mobile material storage needs in order to take the material from two blast cycles about 400 m^3 of material handling capacity.

Vehicles for the drilling of the blastholes, a robot vehicle with robot arms for the charging of the blastholes and wiring the detonators and the blast circuit, LHDs for loading and units for roof support installation are needed. All vehicles are teleoperated.

As solutions for the teleoperation and automation of drill jumbos, LHDs and roof support installation units are existent, they will not be described in this paper.

SAFER CHARGING OF EXPLOSIVES WITH ROBOTS

ABB started in 2014 with the idea of using a robust industrial robot system for the charging of explosives in underground roadway development. Nikolaus Sifferlinger was the 2014/2015 project manager with the Rock Tech Centre in Sweden to develop concepts for such a robotic charging systems (Rock Tech Centre, 2015).

ABB has developed this concept further and tested prototypes in laboratory and test mine (ABB, 2024).

In October 2023 ABB, Boliden and LKAB announced the successful testing of an automatic robot system in a mine, charging the explosives, planting the detonator and connecting the blast circuit wiring (ABB, 2023).

Figures 3 and 4 show the prototype of the vehicle with the two robot arms and the necessary storage of bulk explosives and detonators and wiring for blast circuit. One robot arm does the charging, the second robot arm does the manipulation of the detonators. The arms also do the blast circuit wiring.

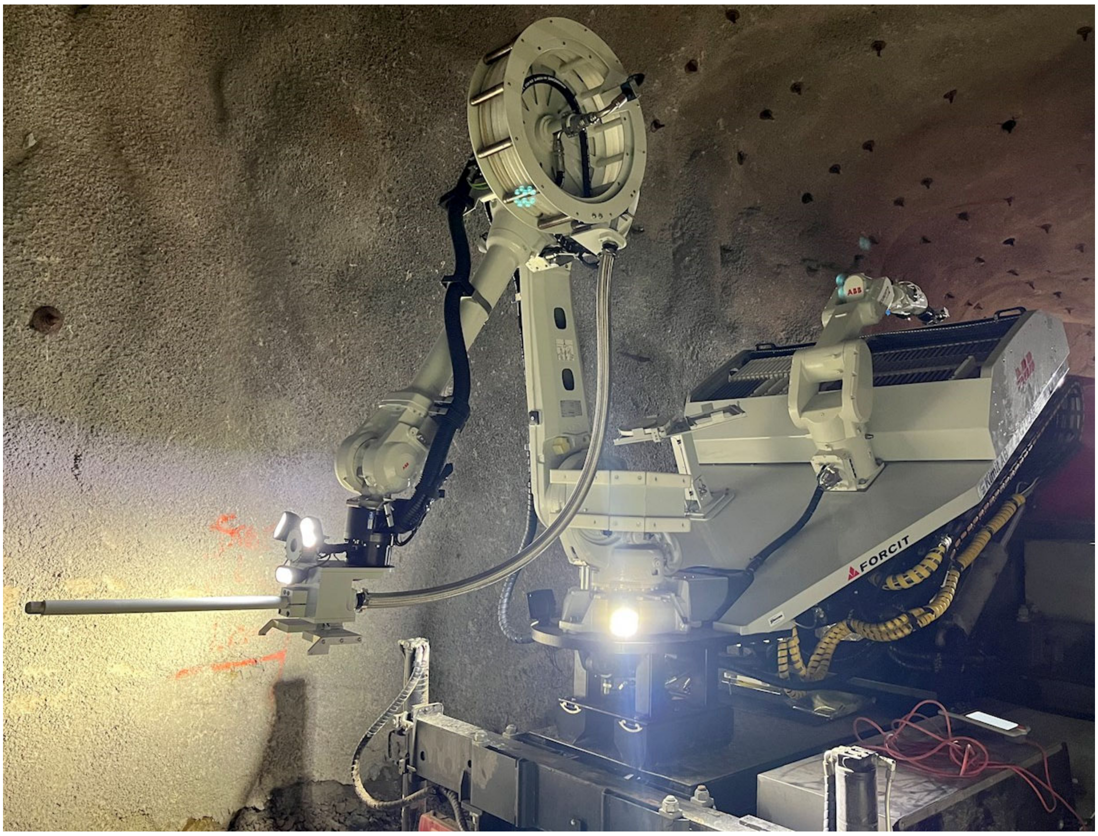


FIG 3 – The charging truck with the robot arms and the storage for bulk explosives and the detonators. The technology includes vision systems and automation solutions to communicate with the truck crane and ABB industrial robotic arm (image courtesy of ABB).

FIG 4 – Robot arm detecting the position of the drilled holes and then does the charging (image courtesy of ABB).

In future wireless detonators will help to reduce the blast circuit wiring (Orica, 2024), which reduces the task for the robot.

MOBILE STORAGE SYSTEM

When no ventilation is allowed for longer periods also the transport and storage system need to be able to handle this situation.

A mobile storage system for 400 m^3 capacity with a size of the loading area of 2 m width and 3 m height would be about 80 m long (Figure 5). There would be a feeder breaker at the entry, the material would be moved with armoured face conveyors. The system would be on caterpillar tracks and would be moved itself when empty.

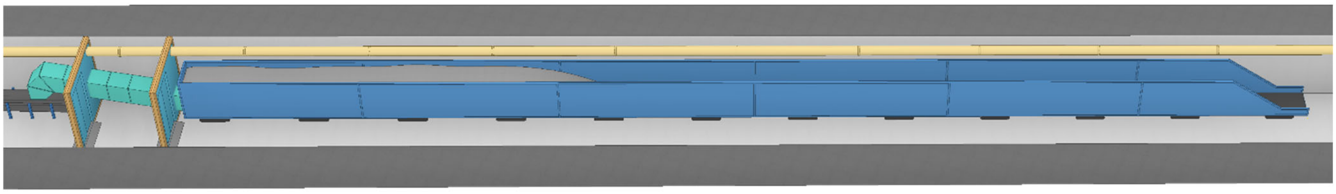


FIG 5 – A proposed mobile storage system concept on caterpillar tracks and flexible in the joints for about 400 m^3 of material (drawing courtesy of E Fimbinger).

The discharge of the mobile storage system onto the conveyor belt outside the ventilation wise enclosed area can only happen in the designated time slots. In the other time it needs to be closed by technical means to contain the blast fumes.

With the mobile storage system being about 80 m long and in the begin of about 40 m in front for the roadway development process (enclosed section in the begin 120 m) with the advance the roadway the distance in front of the mobile storage system in direction to the face will grow up to about 200 m. More than 200 m distance between face and breaker of the mobile storage system will lead to long haulage for the LHDs.

The total length of the ventilation wise enclosed area will grow from about 120 m to 320 m before a move of the mobile storage system and the mobile ventilation bulkheads will be necessary.

When we expect to double our daily advance rate from about 12 m to 24 m a move of the complete system will be necessary about every eight days.

A time study for this concept will be done as a Master thesis at Montanuniversitaet Leoben in the coming 12 months.

MOBILE VENTILATION BULKHEAD SYSTEM

To keep the toxic blast fumes until the next ventilation time slot in the roadway development section a mobile ventilation bulkhead system is needed. This bulkhead needs to withstand the blast wave of the blasting at the face and keep all fumes contained (Zharikov and Kutuev, 2020).

The distance between the ventilation bulkhead and the point of blasting in the face varies between 120 m and 320 m.

Figure 6 shows a first concept of such a ventilation bulkhead.

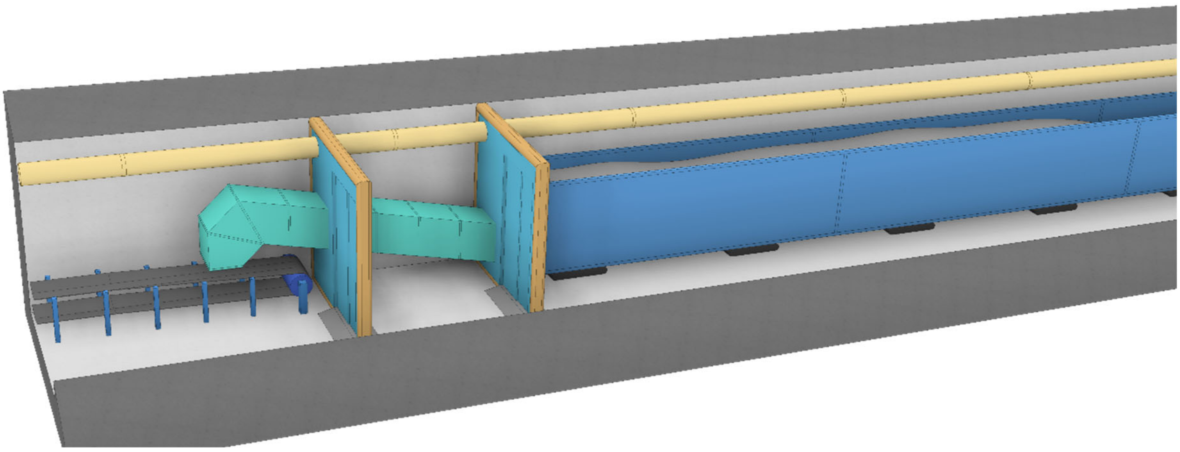


FIG 6 – First concept of a mobile ventilation bulkhead utilising two walls (drawing courtesy of E Fimbinger).

The detailed layout of this ventilation bulkhead system is not part of this paper. Further research is initiated at Montanuniversitaet Leoben.

TELEOPERATION AND AUTOMATION

The operation of such a robotised roadway development system can be done via teleoperation from a control centre. For LHDs and Drill Jumbos teleoperated solutions are in operation (Sandvik, 2023). For roof support teleoperated shotcrete units and roof bolters are also available (EPIROC, 2022).

The robotic charger for explosives has been described above.

The tools for teleoperation and automation are available and can be applied to the project.

RELIABILITY AND MAINTENANCE

A key for the proposed method is the high availability of the equipment during operation. If a component fails during the time where there is no access to human maintenance personnel because of no ventilation of the blast fumes, the system would be stopped until the next possible ventilation time slot. Redundant additional units could reduce the probability of failure during this time.

It has to be noted the humans for task of installation, maintenance and repair cannot be replaced in mining for many years to come.

So automated and robotised equipment can be operated without human interference until the moment it needs maintenance.

CONCLUSIONS

By robotising the drill and blast operation and introduction of mobile storage systems and mobile ventilation bulkheads, it will be possible to increase the advance rates in deep mining roadway development. Doubling the advance rate is possible.

At present status of all the involved equipment this will be achievable within the next decade.

Note: This is the idea of researchers with a long experience in developing mining and tunnelling equipment in the industry. It is presented for discussion.

ACKNOWLEDGEMENTS

Thanks to ABB, Boliden, Forcit and LKAB to invest into the research and development of robotic charging of explosives and detonator handling and wiring for the safety in mining and sharing the results. All used information is public.

REFERENCES

ABB, 2023. ABB, Boliden and LKAB complete successful testing of industry-first automated robot charger for increased safety in underground mines, press release 30 October 2023, ABB. Available from: <https://new.abb.com/news/detail/108967/abb-boliden-and-lkab-complete-successful-testing-of-industry-first-automated-robot-charger-for-increased-safety-in-underground-mines> [Accessed: 10 February 2024].

ABB, 2024. Automated robot charger pilot solution for remote blasting of rock face, ABB. Available from: <https://new.abb.com/mining/mineoptimize/systems-solutions/mining-automation/mining-robots-move-people-away-from-unsafe-areas-and-towards-the-autonomous-mine-vision> [Accessed: 10 February 2024].

EPIROC, 2022. Epiroc's new Boltec with Auto Bolt Reload redefines safety and productivity within rock reinforcement, 15 September 2022, EPIROC Newsroom. Available from: <https://www.epiroc.com/en-ye/newsroom/2022/boltec-auto-bolt-reload-redefines-safety-and-productivity> [Accessed: 14 April 2024].

Narimani Dehnavi, R, 2024. Development of a quantitative risk assessment method to address the rock mechanics issues of applying TBMs in deep mines, Doctoral Thesis, Montanuniversitaet Leoben.

Orica, 2024. WebGen™ 200 – Increased Versatility with New Features for Greater Possibilities; second generation Wireless Initiating System, Orica. Available from: <https://www.orica.com/products-services/blasting/wireless/how-it-works/webgen-200/webgen-200> [Accessed: 10 April 2024].

Rock Tech Centre, 2015. Safer Charging, final report, November 2015 (Rock Tech Centre: Stockholm).

Sandvik AB, 2023. Sandvik wins major order from LKAB for automated loaders, 11 December 2023, Sandvik AB. Available from: <https://www.home.sandvik/en/news-and-media/news/2023/12/sandvik-wins-major-order-from-lkab-for-automated-loaders/> [Accessed: 14 April 2024].

Sifferlinger, N A, 2023. Challenges in mechanical excavation in mining and the need for robotization of tool change, in *Proceedings of the 26th World Mining Congress 2023*. Available from: https://wmc2023.org/proceedings

Zharikov, S and Kutuev, V, 2020. On the issue of defining safe distances and overpressure under impact of shock air blast wave (Magnesitovaya mine), in *VIII International Scientific Conference "Problems of Complex Development of Georesources" (PCDG 2020), E3S Web Conf*, 192:01027. https://doi.org/10.1051/e3sconf/202019201027

Radar guided blasthole drilling improves product recovery

W Stasinowsky[1], B Zhou[2], M van de Werken[3], I Mason[4] and J Hargreaves[5]

1. Senior Research Geophysicist, CSIRO, Brisbane Qld 4069.
   Email: wayne.stasinowsky@csiro.au
2. Senior Principal Research Geophysicist, CSIRO, Brisbane Qld 4069.
   Email: binzhong.zhou@csiro.au
3. Senior Electronic Engineer, CSIRO, Brisbane Qld 4069. Email: matt.vandewerken@csiro.au
4. Professor Emeritus, School of Geosciences, The University of Sydney, Sydney NSW 2006.
   Email: iain.mason@sydney.edu.au
5. Director, JEH Radar Consulting Ltd, Breekamp 33, Beilen 9412AM, The Netherlands.
   Email: jonathan@jehradarconsulting.com

INTRODUCTION

A critical step in open cut coal mining is clean removal of the overburden. This is usually achieved by drilling, blasting and digging. A key part of this process being successful is to stop drilling at the correct blast 'stand-off distance'. The stand-off distance is the distance between the base of the drilled blasthole and the top of the coal horizon to be mined. Having this correct provides a protective cap of rock above the coal horizon so that the blast will fracture all the overburden without damaging the coal horizon or mixing it with the overburden. Drilling beyond the correct stand-off distance causes the blast to continue into the coal horizon, damaging it and mixing it with the overburden, leading to significant losses of coal product. Conversely, drilling short of the correct stand-off distance results in additional work to remove the intact overburden.

It has been estimated that incorrect stand-off distances on blastholes cost the Australian coal industry between 5 per cent and 20 per cent of total coal production (Scott and Wedmaier, 1995). This translates into a loss of billions of dollars per annum, in addition to the permanent loss of millions of tons of the precious resource.

To minimise losses and stop at the right stand-off distance (~1 m), the coal seam depth must be known accurately (<=0.2 m) at the point of drilling. Coal seam models are difficult to generate accurately because they are often extrapolated from data in widely spaced exploration holes or from mapping faces on previously exposed benches. Drillers often rely on drilling to the top of the seam every five or so holes and estimating the correct depth until they again drill to the top of the coal. This process itself creates problems with stand-off distances in many of the holes. Drillers have also tried unsuccessfully to automate stratigraphic touch judging for 80 years, to update overburden maps in near-real time, to predict target depth of the next hole, by feeding forward results from the drilled neighbouring holes.

Also over the past 80 years, engineers have found it just as hard to attach probes downhole to use geophysical fields that sense ahead of a drill bit, as it is hard to read the interactions with the target horizon in time to control final approach. Rig logs such as weight on bit, torque, air pressure and penetration rate, were designed to protect the rig and not designed for rock recognition. Drill rig log messages are mixed when applied to geology, and success has been unreliable.

RADAR GUIDED BLASTHOLE DRILLING SYSTEM

In seeking a solution to the coal-top problem, CSIRO has developed a technique based on guided borehole radar (BHR) wave imaging to predict the coal seam top in real-time, while drilling blastholes (Zhou and van de Werken, 2015, 2019; Zhou, van de Werken and Huo, 2020). The method integrates a BHR with a steel drill-string to induce a guided wave axially along the drill-string. These guided BHR waves are formed by Goubau waveguides (Goubau, 1950; Barlow, 1971; Laurette *et al*, 2012). The drill-rod ahead of the BHR, including the drill bit becomes part of the radiating antenna. When the guided wave travels to the end of the drill bit, some energy is reflected, and the remainder radiates from its end. The radiated energy is reflected by geological discontinuities such as the top of the coal, and the reflected energy is recorded by the integrated BHR system. Thus, integrating the BHR with the steel drill string affords the potential to image ahead of the drill bit. This is illustrated by the numerical modelling result shown in FIG **1**.

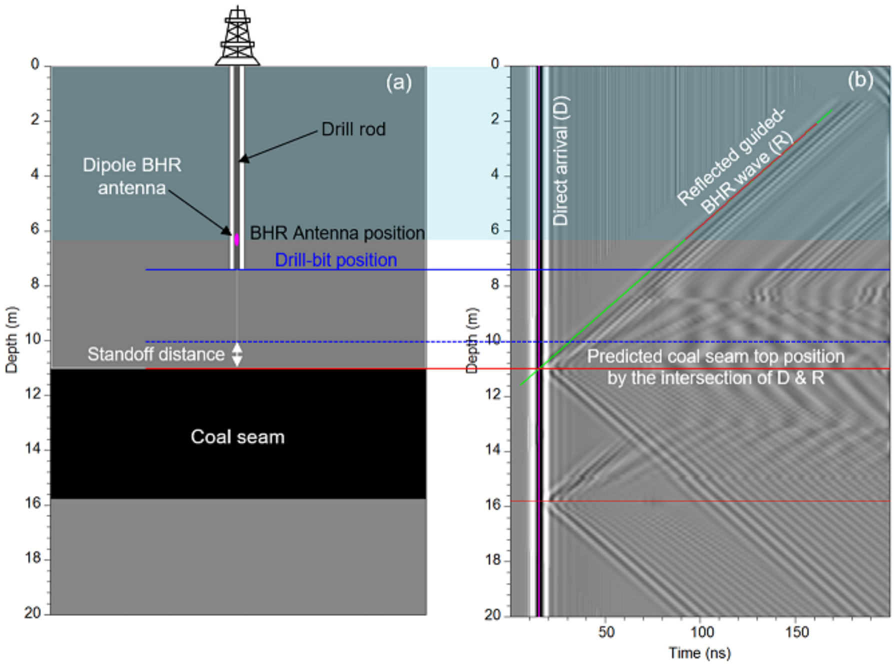


FIG 1 – Illustration of coal seam top prediction using reflected forward-looking guided borehole radar (BHR) wave through integrating a conventional BHR with a steel drill rod: (a) The geological model for the guided BHR wave imaging modelling; (b) The simulated profile of the guided BHR wave imaging based on the model in (a), indicating that the accurate position of the coal seam top can be predicted by the intersection position of the direct and reflected guided BHR waves.

The coal-top prediction system based on guided radar waves, mainly consists of three subunits as shown in FIG **2**. The Cab Control Unit (1) is a user interface that controls the data acquisition of the Downhole Unit (3) via the Top Comm-Relay Unit (2). It also performs data calibration for each working site, automatic real-time data processing, display and target tracking and provides the driller with a warning that they are approaching the recommended coal seam distance from the drill bit.

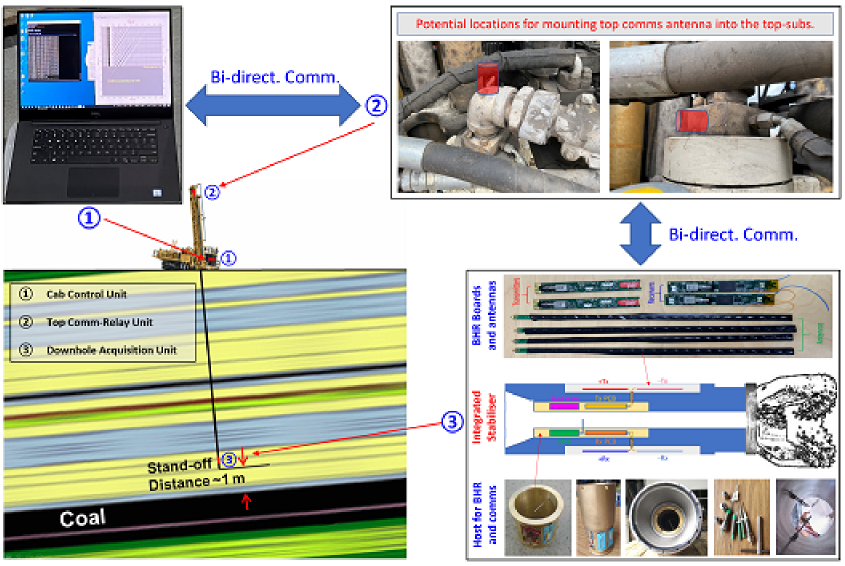


FIG 2 – Illustration of coal seam top prediction system: (1) Cabin user control unit; (2) wireless communication relay unit at the top of drill string; (3) Downhole data acquisition unit behind the drill bit.

The Top Comm-Relay Unit (2) is a wireless relay station to link the communication between the Downhole Acquisition Unit (3) and the Cab Control Unit (1). The wireless communication and data transmission are realised by transmitting GHz frequency electromagnetic (EM) waves through the internal cavity of the drill-string.

The Downhole Unit (3) contains the radar electronics and antennas for both transmitting and receiving radar signals as well as the downhole communications electronics for transmitting the data up the drill string to the surface and batteries for self-contained power. The batteries have enough capacity for several days of continuous operation and are high temperature rated.

FIELD TRIALS ON AN RAB DRILL RIG

A fully waterproof radar was embedded on a stabiliser of an RAB blasthole drill rig and the integrated radar was trialled on a blast bench at a support mine. Although there were issues with the poor connection between the antennas and the radar boards, a BHR data set was logged from a trial blasthole using the integrated BHR on the stabiliser. The results are shown in FIG **3**. FIG **3**a is the raw data, dominated with the direct arrival. After suppressing the direct arrival using the average filtering technique, the enhanced look-ahead waves (reflections from the strata ahead of the drill bit) are marked with the green and red arrows in FIG **3**b. The lower red arrow points to the look-ahead wave from the top of the coal seam. It has a look-ahead capability of ~2 m. Improvements the hardware and processing made since that time are expected to allow an even greater look ahead distance.

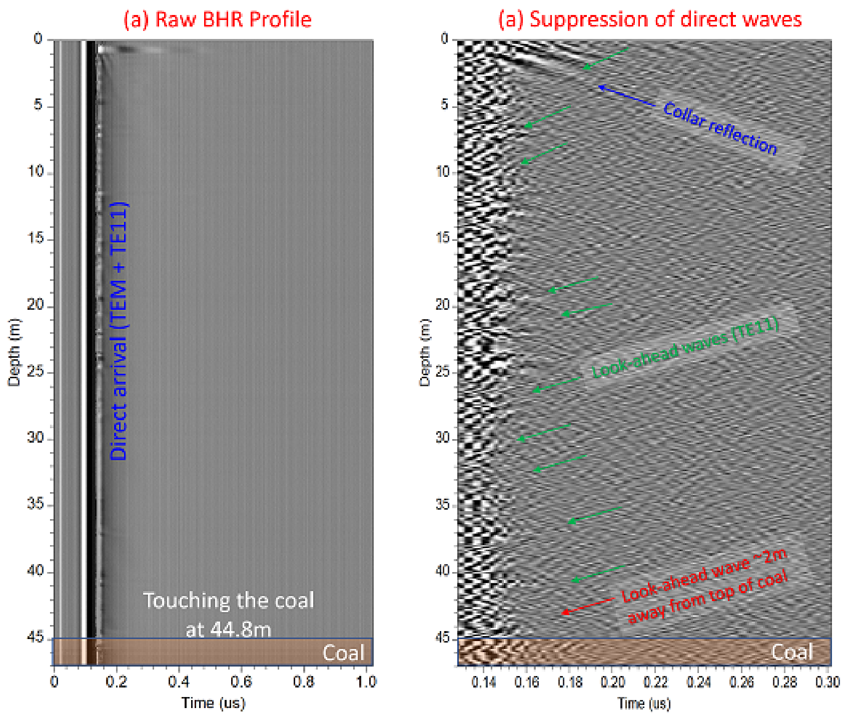


FIG 3 – BHR profile logged from a trial blasthole using an integrated BHR on the stabiliser: (a) Raw BHR profile; (b) The suppression of direct arrival enhances the look-ahead waves as marked by the green and red arrows.

Improvements currently under development will bring the technology to a technology readiness level of 7 (TRL7), ie prototype demonstrated in an operational environment.

CONCLUSIONS

A radar-guided blasthole drilling system has been developed for predicting the top of coal seams in real-time while drilling blastholes. Field trials clearly demonstrate the feasibility of using the guided radar waves for coal-top prediction while drilling blastholes in typical open cut environments. In principle, the technique sounds easy but is not straightforward in practice. There are several issues to overcome, including but not limited to:

- Integration of the radar into the drill-rod.
- Optimisation of the radar antenna design to improve the generation of the look-ahead waves.
- Communication of the downhole radar recordings back to the driller in real time.
- Enhancing the look-ahead events to detect the top of coal.
- Calibration of the look-ahead events with the mine site geology to identify the coal seam reflections from other geological reflections.
- Automation of seam-prediction.
- Developing a warning system that is practical for drillers without compromising their productivity.

The current project is addressing these technical and engineering issues and has made significant progress. This technique can also be extended to drilling in metalliferous mining and civil engineering. Conceivably, future adaptions may facilitate automatic drilling of blastholes.

Success in this project will enable a significant step in making this technology available in practice, so substantial mineral resources can be saved, and the mines can become more productive and more profitable.

ACKNOWLEDGEMENTS

This research was supported by the Australian Coal Association Research Program (ACARP). The following people are thanked for their strong interest and support for the work reported here: Peter Chern of Coronado Global Resources Inc, Elsie Gretton and Rick Walker of Idemitsu Australia Resources Pty Ltd; Noel Pranoto, Barry Lay, Kirsty Liddicoat and John Centofanti of BHP Coal; Richard Ruddock of Rio Tinto Coal; Patrick Tyrrel of ACARP; David Drakeley of FieldCrew; David Edward and Troy O'Reilly of Meandu Mine (Stanwell Corporation Ltd).

REFERENCES

Barlow, H M, 1971. Screened and unscreened axially-cylindrical surface waves, *J Phys D Appl Phys,* 4:372–380.

Goubau, G, 1950. Surface waves and their application to transmission lines, *J Appl Phys*, 21:1119–1128.

Laurette, S, Treizebre, A, Bourzgui, N E and Bocquet, B, 2012. Terahertz interferometer for integrated Goubau-line waveguides, *Progress in EM Research Letter,* 30:49–58.

Scott, A and Wedmaier, R, 1995. The Assessment and Control of Coal Damage and Loss, Final Report for ACARP Project C21005.

Zhou, B and van de Werken, M, 2015. Conductively guided borehole radar wave for imaging ahead of a drill bit, *IEEE Geosci Remote Sens Lett,* 12:1715–1719.

Zhou, B and van de Werken, M, 2019. Real-time prediction of coal top through guided borehole radar wave imaging for open cut blast-hole drilling, Final Report for ACARP Project C26022.

Zhou, B, van de Werken, M and Huo, J, 2020. Coal top detection by conductively-guided borehole radar wave imaging for open cut blast-hole drilling, *Geophysical Prospecting*, 68:982–998.

Robust flexibility – a methodology for agile systems engineering in mining

Z Tabor[1] *and D Brown*[2]

1. Systems Engineer, Nova Systems, Fremantle, WA 6160.
   Email: zachary.tabor@novasystems.com
2. Systems Engineer, Nova Systems, Fremantle WA 6160.
   Email: daniel.brown3@novasystems.com

INTRODUCTION

Projects must be flexible to account for the rapid development of new technologies and changing stakeholder expectations. Coupled with calls for bleeding-edge solutions, customers, shareholders, and regulators demand robust, safe products and systems-of-systems. Developing and integrating these solutions is becoming increasingly complex and maintaining the flexibility required to 'pivot' to effective solutions can be a serious challenge. The necessary flexibility is fundamental to the Agile ethos, and this family of methodologies therefore offers a potential solution to this challenge (Beedle *et al*, 2001). These have traditionally been delivered with systems engineering applied through a Waterfall methodology. Agile Systems Engineering combines both approaches and presents a means to achieve these goals without compromising flexibility, quality or safety. A robust methodology for the application of Agile Systems Engineering is required to enhance practical outcomes and reduce risk for real-world mining projects.

Any Agile Systems Engineering approach requires incremental implementation due to the significant cultural and mindset shift from a traditional Waterfall approach. An Agile Systems Engineering methodology for the mining industry is based on a select few critical improvement areas. The eight core aspects of Agile Systems Engineering established by (Dove *et al*, 2023) provide a solid foundation for this work: Agile Operations Concept, Product Line Architectures, Shared-Knowledge Management, Continual Integration and Test, Common-Mission Teaming, Iterative Incremental Development, Attentive Decision-making, and Attentive Situational Awareness. From this foundation, this paper identifies three aspects as critical improvement areas that will enable interested parties within the mining industry to begin adopting Agile Systems Engineering methods for their projects and products. These selected aspects are justified by real-world projects, practical lessons learned, and literature that addresses the challenges of adopting agile methodologies.

The generalised methodology for mining is built around the following aspects: Continual Integration and Test, Iterative Incremental Development, and Attentive Decision-making. These aspects represent the opportunities for greatest return-on-investment for the mining industry. The selected aspects are supported by the establishment and utilisation of integrated project teams, the implementation of contemporary Test and Evaluation methods, and the use of Digital Engineering capabilities to harness intelligent digital twins.

From the starting point outlined in this paper, the methodology is intended to spark discussion and reflection, and provide some initial guidance for those in the mining industry that are seeking to leverage the benefits of Agile Systems Engineering but are unsure of where to start. The methodology will grow and evolve as Agile Systems Engineering is implemented more broadly; active discussion is encouraged. It is hoped that the framework will also inspire industry leaders to approach Agile Systems Engineering as a feasible undertaking, worthy of investment.

AGILE SYSTEMS ENGINEERING

At the time of writing, Waterfall remains the default methodology for project delivery, with more projects completed using Waterfall than all other methodologies combined (Project Management Institute, 2020); the approach was most succinctly defined, but also heavily criticised, by Winston Royce in the early 1970s (Royce, 1970). In his paper, Royce identifies one of the critical shortcomings of the Waterfall method – a vulnerability to major changes and redesign. This has been borne out through experience as an increasing number of projects face challenges initiated by volatility and change (KPMG Australia and AIPM, 2022). Combined with the inherent technological challenges that have emerged as a result of rapid innovation (San Cristobal *et al*, 2018), overall project complexity appears to be increasing.

Systems Engineering has traditionally been a practice that attempts to mitigate complexity through robust processes and practices. Given the predominance of the Waterfall methodology, much of Systems Engineering's development as a discipline has been aligned to a linear, sequential framework that aligns with Waterfall. In the sub-disciplines of Test and Evaluation (T&E), System Safety and Requirements Management, this linearity is less pronounced but still present.

To address the inherent challenges of the Waterfall methodology, a number of alternative methodologies have been developed – some are continuations of business practices that are decades old (Kanban/Lean), while some are somewhat more recent developments (Agile, XP Agile). Crucially, as products become more complex and integrated, the inflexibility of Waterfall creates more problems than it addresses; developing software using a Waterfall methodology can introduce serious inefficiencies, and most products available today incorporate some sort of digital component (Holmes, 2019).

Tenets of Agile Systems Engineering

As alternative project management methodologies have been explored – including the Agile family of methodologies – the development of the Systems Engineering discipline has attempted to keep pace; this is evidenced by the formation of an Agile Systems Engineering working group (INCOSE, 2024). Utilising the foundations established by the INCOSE working group, this paper aims to utilise real-world learnings to make Agile Systems Engineering a reality for the mining and resources industry.

The findings of this paper are largely based on the eight core tenets of Agile Systems Engineering established at the 2023 INCOSE Symposium (Dove *et al*, 2023); their paper clearly outlines the core aspects and provides a succinct description of each of them. A diagrammatic representation of the core aspects outlined in this paper is show in **Error! Reference source not found.**. The work of Rick Dove and Bill Schindel is fundamental to the methodology in this paper.

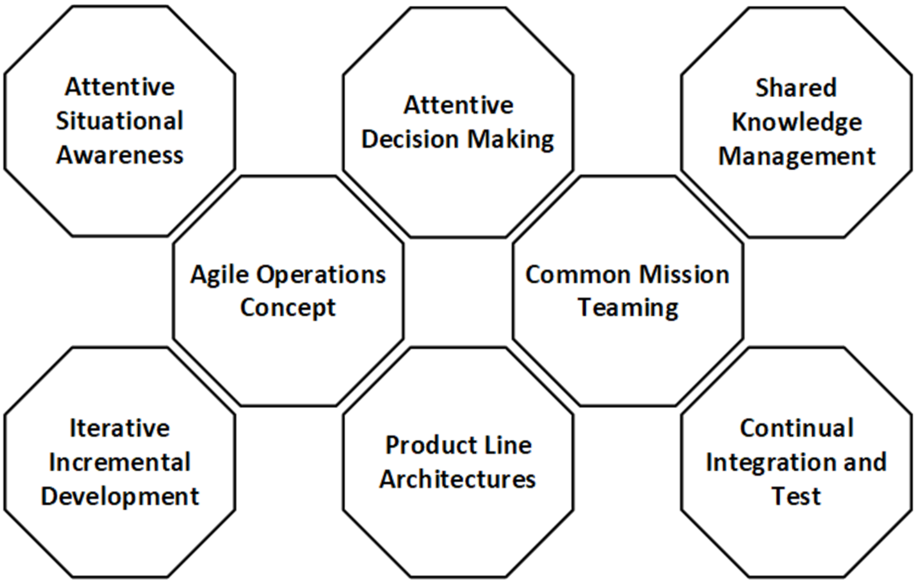


FIG 1 – The eight core aspects of Agile Systems Engineering, adapted from (Dove *et al*, 2023).

AGILE SYSTEMS ENGINEERING IN MINING

Most work on Agile Systems Engineering to date has been aimed at implementation in the defence and aviation industries, with mixed success (Dove and Schindel, 2017) – these industries have incredibly stringent assurance processes and generally display a very high level of Systems Engineering rigour. While this high standard of practice may seem to be a benefit for the implementation of Agile Systems Engineering, in some ways it may be a hindrance. These industries have robust established processes that are tailored to fit Waterfall execution, and embracing the cultural changes required by Agile execution can prove difficult.

While the mining and resources industry in Australia has a very strong regulatory framework, coupled with effective legislation, systems assurance maturity in the industry has not yet reached the level of the aforementioned sectors. While this may seem to be a criticism, this is in fact a key argument in favour of adopting more contemporary and flexible ways of working, including Agile Systems Engineering principles. With a smaller 'process-debt' and a diverse project portfolio, mining and resource companies can afford to adopt a scalable approach to Systems Engineering, prioritising investment in assurance activities that mitigate primary risks and deliver increased efficiency.

Utilising the Agile Systems Engineering Life Cycle Methodology (ASELCM) (Dove and Schindel, 2019) as a basis, specific modifications can be made that utilise the strengths of the mining industry as it currently stands. These modifications are built around three key improvement areas:

- Iterative, Incremental Development.
- Continual Integration and Test.
- Attentive Decision Making.

The key improvement areas are shown in **Error! Reference source not found.**. These improvement areas have the potential to deliver significant value to the mining and resources industry as they address primary execution hazards encountered during the development of products and projects: misalignment of scope with stakeholder needs, failure to meet an established scope, and indecision or flawed decision-making. While it would be a bold claim to insist that improvements in the above areas are ensured by adoption of an Agile Systems Engineering approach, it would be more accurate to state that the highlighted aspects would be a valuable tool in mitigating these risks. As the scope of this paper is limited, the methodology outlined does not include implementation methods, and only the specific merits and difficulties attached to the highlighted aspects are included here.

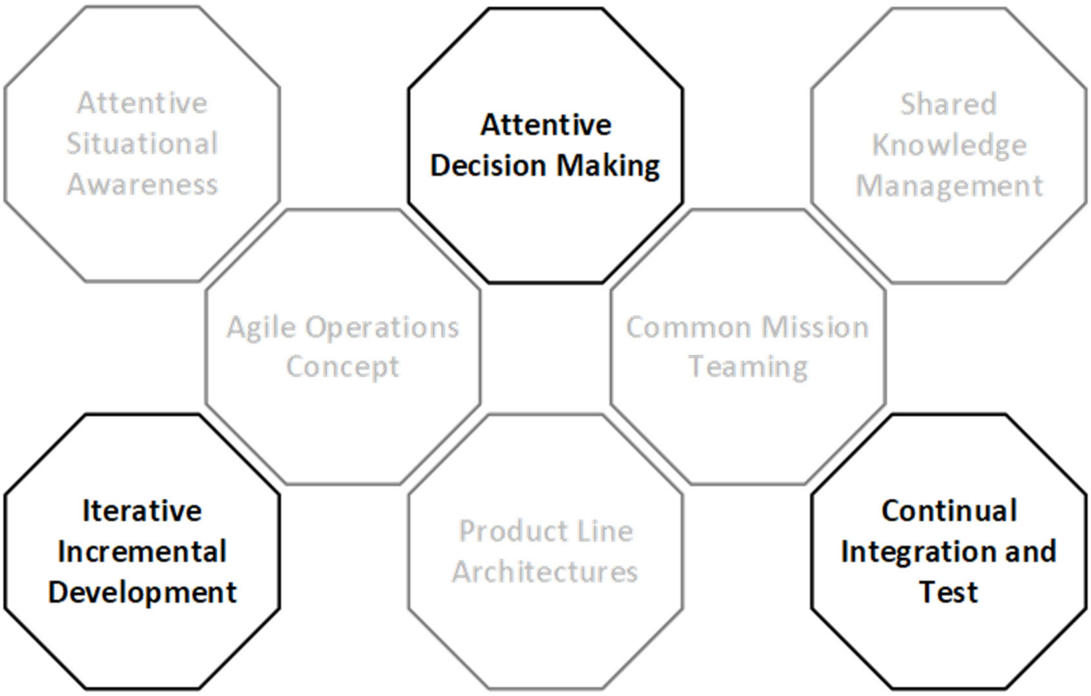


FIG 2 – Down selected aspects of Agile Systems Engineering for Mining.

Adopting an Agile methodology in general presents significant challenges, and many attempts at doing so end up developing a Water-Scrum-Fall approach (West, 2011) – a hybrid approach that includes elements of both the Waterfall and Scrum Agile methodologies. This approach delivers benefits over a fully Waterfall methodology but does not realise many advantages of a fully Agile Methodology. Crucially for the methodology set out in this paper, it is assumed that the adoption of Agile Systems Engineering is undertaken as part of a wider organisational move or in the context of smaller pilot projects. As established by Dove *et al* (2023) 'big bang concurrent implementation of all aspects is not necessary to gain agility benefits'.

Iterative incremental development

To understand the benefits of iterative, incremental development, there must first be a clear understanding of the meaning of the term. These definitions are drawn from the explanations provided in *Learning Agile* (Stellman and Greene, 2014). Iterative development can be regarded as a process of continuous refinement. Each development pass is undertaken with the understanding that the product will be deficient in one or many areas. The goal of this process is not to deliver a finished product or feature, but to deliver an *improved* one. Incremental development, on the other hand, is focused on the delivery of defined subsets of functionality. Each increment is fully developed and tested as part of this process. While these two approaches may seem contradictory, they are in fact complementary. By utilising iterative development within each increment, fully functional components of the product can be delivered in stages, eventually comprising a completed system. Even in intricately interconnected and complex systems, this approach can be utilised to maximise compatibility – the interfaces of a feature within one subsystem can be tested and developed against the interfaces of another feature within a different subsystem during development, even if the other subsystem is no longer in active development.

Within the specific context of Systems Engineering for mining, this approach is appropriate for the management of assurance processes and development of assurance documentation. These activities are heavily interconnected, which can present difficulties during Waterfall execution; for example, during the early stages of a project it is necessary to develop comprehensive requirements, an initial hazard assessment, and an early test program outline. These can be developed sequentially, but taking an iterative and incremental approach to these activities allows them to be developed in parallel with a deeper understanding of the inter-relation between them.

This is accommodated by a move away from the traditional Big Requirements Up Front (BRUF) method of developing all initial needs and requirements at once and a move towards the development of User Stories (Dove and Schindel, 2017). The focus on user stories allows more complex interactions to be captured, which in turn provides a wealth of information for the development of requirements, hazard assessments and practical test cases.

Accepting the iterative nature of Agile Systems Engineering also permits an assurance program to be flexible in the face of a changing environment or fluctuating user needs. While this flexibility comes with the caveat of significant re-work, it enables the system to remain relevant to developing user stories; delivering a completed system is only worthwhile if it suits the user. This attitude has been exemplified by the work of SpaceX on its Falcon 9, Falcon Heavy and Dragon programs; operating in a heavily regulated and controlled industry, the company has demonstrated the value of iterating its designs without compromising safety or commercial returns (Berg, 2019).

Continual integration and test

A common shortcoming of Waterfall projects is the practice of waiting for a completed product before initiating user testing. While this minimises the schedule and cost impact of testing activities by constraining them to a narrowly defined scope, it can severely hamper the efficacy of this testing, particularly regarding user experience and system processes. By conducting a continual test program, utilising product functionality increments, flawed interfaces and processes can be identified and rectified during development rather than during Acceptance Test and Evaluation (AT&E). As stated in *Learning Agile* (Stellman and Greene, 2014):

> *'The best way we have for users to judge whether or not the team is building valuable software is to put working software in their hands as frequently as possible.'*

By testing during development, user stories, requirements and hazard controls can be validated against user feedback, which in turn can inform design and process changes. Crucially, this testing must be continual – ideally some form of the product should be provided to representative users for every increment.

When operating in complex organisations or developing particularly complex products the prospect of testing an incomplete system in a representative environment can be a daunting prospect – live production environments are rarely tolerant of the disruptions caused by thorough testing. In this scenario, synthetic test environments can offer a reasonable substitute for the real world. These synthetic environments are becoming increasingly viable as technology advances, especially when enabled by Artificial Intelligence (AI). However, it should be noted that even an advanced model of a given system-of-systems must be validated against real-world data; this can be an entire project unto itself. An example of an existing digital synthetic test environment is the Lockheed Martin Aeronautics Agile Non-Target Environment (ANTE) (Dove, Schindel and Garlington, 2018). This environment establishes a common schema for software components being integrated into flagship systems such that these components can be tested thoroughly through simulation; this testing occurs at key points during product development to verify functionality and interface compatibility.

Synthetic test environments do not have to be advanced digital systems – the concept of an 'iron bird' is well established in the aviation industry, and the defence industry is increasingly open to adopting sensor-and-effector-agnostic platforms for the purpose of testing (Dove, Schindel and Scrapper, 2016). Utilising these test environments comes at the cost of operational accuracy and increased resource commitments but offers representative real-world performance data without disrupting existing environments.

Attentive decision-making

> *'a standardized process can provide a guideline to the workers on how to deliver an adequate level of performance in a routine setup, but it may entail production inefficiencies due to its lack of responsiveness to local information'* (Li, Mukherjee and Vasconcelos, 2022)

To accommodate Agile Systems Engineering methods, a degree of cultural change is required within the adopting organisation – this change is required not just in the undertaking project team, but their superiors and stakeholders as well. A certain level of trust in the project team is required for Agile Systems Engineering to deliver effective results. For example, the Scrum methodology depends on the ability of the Product Owner to make decisions on behalf of the business, including accepting completed work. An effective Agile team can be trusted to ignore 'distractions' – reporting, support for other projects, administrative overhead – where possible. This minimises interruptions to the Observe-Orient-Decide-Act (OODA) loop (Ryder and Downs, 2022; Lyells, Angier and Epps, 2018) and allows the team to pivot their approach depending on new or changing information. With the promise of AI-enabled business processes (Manyika and Sneader, 2018), the human element of this OODA loop may soon be the weakest; this can be mitigated by adopting a more Agile mindset and allowing project teams to make informed decisions without requiring input from a larger hierarchy. These decisions may include a determination of the best process to follow when resolving a given challenge: Waterfall, Agile, or hybrid; to be truly flexible, an organisation must be comfortable with any combination of methods (West, 2011).

It should be noted that Agile decision-making does not require full project autonomy – checks and balances are critical to organisational success and form an important aspect of a functional Agile team. Project accountability is primarily achieved through the goals set for each increment – because each increment is required to deliver functionality of some description, it is quickly apparent if the project is not achieving its goals (Carlson, 2017). To enable this, the parent organisation is required to alter applicable Key Performance Indicators (KPIs) for Agile projects. KPIs related to cost and schedule will still apply, but they must be adapted to reflect sprints or other increments. Crucially, KPIs must deliver value to the project, not just the organisation. As established by the British economist Charles Goodhart, target metrics can drive key behaviours, both positive and negative (Goodhart, 1975). By carefully selecting these metrics, desirable behaviours and outcomes can be established or maintained within a project team.

The freedom required by Agile methods may cause consternation for some organisations that are traditionally bound by internal process – often the root of this concern is the financial and reputational risk associated with critical project decisions. Agile Systems Engineering can mitigate this risk by aligning assurance processes with rapid decision-making. This is the key difference between normal decision processes and 'attentive decision-making'; an attentive decision ensures that the decision is made with as much information about the impact of each option as possible, not just to the project/product but also to internal processes. For those familiar with Systems Engineering as a discipline rather than a process, this is not dissimilar to the usual 'tailoring' process undertaken at appropriate stages of a Waterfall project – the difference with Agile Systems Engineering is that this process is undertaken for every key decision to determine which tools and methods can deliver the most robust assurance outcomes for each option.

Enabling practices

The execution of an Agile Systems Engineering approach is not just composed of methods and processes, but rather requires enabling and supporting practices to accommodate a flexible assurance program. Several key elements of this support system are laid out in the following sections.

Systems engineering information management

To accommodate rapid and effective decision-making, information relevant to Systems Engineering processes must be readily available and effectively controlled. Where possible, this should involve the use of digital tools or an integrated development environment. This can be achieved through a Model Based Systems Engineering (MBSE) approach, or by using discrete tools for individual processes.

Robust configuration management is critical to the decision-making process, as poor visibility of the 'current state' and 'future state' of a product or system undermines the project's understanding of any changes. This extends not just to configuration management tools, but also to related processes and policies; assuming that processes are already in place, these need to be reviewed to ensure compatibility with Agile methods. Attempting to manage the configuration of an Agile-developed product using Waterfall-aligned processes may result in unnecessary delays or errors when implementing and understanding changes to the product.

Ongoing life cycle systems assurance

Particularly when developing products and systems for a live production team, integration of operational, maintenance and support teams is critical at all stages of development. During a study of Northrop Grumman's Global Combat Support System – Joint (GCSS-J) group, it was identified that including a consistent set of end-users through increment definition, development and testing delivered improved outcomes (Dove and Schindel, 2017). Understanding not just the functional needs of these users but also their assurance and governance needs allows the project to align with their expectations and minimise the lag time between Initial Operational Capability (IOC) and Full Operational Capability (FOC).

Systems engineering resources

Possibly the most important element of an Agile Systems Engineering approach is the need for a skilled and diverse Systems Engineering team. Especially when employing a Scrum Agile methodology, the ability to re-orient and assign resources according to the most pressing or valuable tasks is hugely important. By shifting the focus from individual disciplines to discrete tasks, interdependencies can be resolved rapidly rather than causing dependency cascades and delays. By coupling this flexible resourcing with cross-specialised systems engineer, a better integrated and more flexible systems assurance program can be achieved. This approach was utilised to great effect by GCSS-J and referred to as 'plug and play' resourcing.

AGILE SYSTEMS ENGINEERING CHALLENGES

Of course, delivering an Agile Systems Engineering effort is much simpler on paper than in the real world – even an incremental approach to longstanding processes and attitudes requires cultural change (de Figueiredo Jr, Rawley and Rider, 2015). Generally speaking, an organisation will tend to favour processes and practices that produce consistent results, even if these results are less beneficial than those produced by more inconsistent methods (Hannan and Freeman, 1977). As many Agile implementations have discovered, the support of a powerful sponsor is critical to success – if this backing is not available, often the best-case scenario is a spirited but unsuccessful implementation leading to Water-Scrum-Fall practices.

Even given the support of a prominent sponsor, there is a danger of over-correcting towards rapid but flawed decision-making and change management; even relatively basic mining operations can be intricate and delicate systems and there are significant dangers involved in adopting an Agile methodology without a rigorous assurance program in place to support it. This is especially true when considering modifications to an existing safety-critical system, or the introduction of new components and interfacing systems to a heavily regulated environment such as heavy rail or process infrastructure. In these situations, the management of operations and regulatory stakeholders must be carefully planned and executed – particularly in the case of external stakeholder without any incentive to adopt an Agile mindset, this can potentially stall an Agile project. Despite this compromise, it is important not to 'trade' assurance for agility. This balancing of agility with assurance also extends to test and evaluation activities undertaken. An increase in test granularity and frequency can deliver greater visibility of system functionality and constraints, provided the organisation can finance and accommodate this testing. If, however, the parent organisation is unable to facilitate thorough testing at high frequency there may be a consequential reduction in test rigour and therefore system confidence. Without the requisite confidence, a system may be refused certification or customer acceptance.

Finally, and perhaps most importantly, an Agile methodology is not universally applicable – some projects are well-suited to a Waterfall methodology. This requires an organisation to provide the flexibility (and trust) to its project teams to determine the best methodology. A key determinant when choosing methodologies should be the rate and complexity of change in the product's intended operational environment. Where changes are relatively infrequent, or where the system's interactions with external changes are readily understood, an Agile methodology can introduce unnecessary risk for relatively little gain.

CONCLUSIONS

While it his has its roots in the world of software, Agile methodologies, and by extension Agile Systems Engineering, can enhance projects and mitigate risks in the mining industry. To realise these benefits, organisations must adapt their current ways of working and develop new concepts and practices. The methodology outlined in this paper has identified the 'low hanging fruit' that can be achieved by project teams that are sufficiently supported by their wider organisation. This methodology is intended to provide the mining and resources industry with a starting point for developing its own policies and processes to accommodate Agile – that is, by identifying individually appropriate means to adopt iterative, incremental development of products, continual test and integration, and attentive decision-making, an organisation can begin to explore the benefits of Agile Systems Engineering.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the ongoing work of INCOSE in developing the Systems Engineering discipline. We would also like to thank Martin Shadbolt and Jon Sciortino for their ongoing support and advice.

REFERENCES

Beedle, M, Beck, K, van Bennekum, A, Cockburn, A, Cunningham, W, Fowler, M, Greening, J, Highsmith, J, Hunt, A, Jeffries, R, Kern, J, Marick, B, Martin, R C, Mellor, S, Schwaber, K, Sutherland, J and Thomas, D, 2001. Manifesto for Agile Software Development [online]. Available from: <http://agilemanifesto.org/> [Accessed: 31 October 2023].

Berg, C, 2019. SpaceX's Use of Agile Methods, *Medium.* Available from: <https://cliffberg.medium.com/spacexs-use-of-agile-methods-c63042178a33> [Accessed: 04 June 2024].

Carlson, D, 2017. Debunking Agile Myths*, CrossTalk: The Journal of Defense Software Engineering*, May, pp 32–36.

de Figueiredo Jr, R J P, Rawley, E and Rider, C I, 2015. Why Are Firms Rigid? A General Framework and Empirical Tests, *Organization Science*, 26(5):1502–1519.

Dove, R and Schindel, B, 2017. Case Study: Agile SE Process for Centralized SoS Sustainment at Northrop Grumman, *INCOSE International Symposium*, 27(1):115–135 (International Council on Systems Engineering: INCOSE). https://doi.org/10.1002/j.2334-5837.2017.00349.x

Dove, R and Schindel, B, 2019. Agile Systems Engineering Life Cycle Model for Mixed Discipline Engineering, *INCOSE International Symposium*, 29(1):86–104 (International Council on Systems Engineering: INCOSE). https://doi.org/10.1002/j.2334-5837.2019.00591.x

Dove, R, Lunney, K, Orosz, M and Yokell, M, 2023. Agile Systems Engineering – Eight Core Aspects, in *33rd Annual INCOSE International Symposium*, 33(1):823–837 (International Council on Systems Engineering: INCOSE). https://doi.org/10.1002/iis2.13055

Dove, R, Schindel, B and Scrapper, C, 2016. Agile Systems Engineering Process Features Collective Culture, Consciousness, and Conscience at SSC Pacific Unmanned Systems Group, in *Proceedings INCOSE International Symposium,* pp 982–1001 (INCOSE: Edinburgh).

Dove, R, Schindel, W D and Garlington, K, 2018. Case Study: Agile Systems Engineering at Lockheed Martin Aeronautics Integrated Fighter Group, *INCOSE International Symposium*, 28(1):303–320 (International Council on Systems Engineering: INCOSE). https://doi.org/10.1002/j.2334-5837.2018.00483.x

Goodhart, C, 1975. Problems of Monetary Management: The UK Experience, *Papers in Monetary Economics*, 1(1):1–20.

Hannan, M T and Freeman, J, 1977. The Population Ecology of Organizations, *American Journal of Sociology*, 82(5):929/964.

Holmes, M, 2019. Microsoft CEO: "Every Company is Now a Software Company" [online], Via Satellite. Available from: <https://www.satellitetoday.com/innovation/2019/02/26/microsoft-ceo-every-company-is-now-a-software-company/> [Accessed: 31 October 2023].

INCOSE, 2024. Agile Systems and Systems Engineering Working Group [online], International Council on Systems Engineering (INCOSE). Available from: <https://www.incose.org/communities/working-groups-initiatives/agile-systems-se> [Accessed: 4 April 2024].

KPMG Australia and Australian Institute of Project Management (AIPM), 2022. The State of Project Management in Australia 2022 – Leading projects through volatility, KPMG, Australian Institute of Project Management (AIPM). Available from: <https://info.aipm.com.au/hubfs/Reports%20and%20major%20content%20assets/The%20State%20of%20PM%202022%20Report%20FINAL.pdf>

Li, J, Mukherjee, A and Vasconcelos, L, 2022. What Makes Agility Fragile? A Dynamic Theory of Organizational Rigidity, *Management Science*, 69(6):3157–3758.

Lyells, R, Angier, R and Epps, B, 2018. Creating Decision Guidance for Applying Agile System Engineering, *INCOSE International Symposium*, 28(1):655–670 (International Council on Systems Engineering: INCOSE). https://doi.org/10.1002/j.2334-5837.2018.00507.x

Manyika, J and Sneader, K, 2018. AI, Automation, and the Future of Work: Ten Things to Solve For, *McKinsey & Company – McKinsey Global Institute*. Available from: <https://www.mckinsey.com/featured-insights/future-of-work/ai-automation-and-the-future-of-work-ten-things-to-solve-for>.

Project Management Institute, 2020. Future-Focused Culture, Pulse of the Profession Report 2020.

Royce, W, 1970. Managing the Development of Large Software Systems, Los Angeles, IEEE.

Ryder, M and Downs, C, 2022. Rethinking reflective practice: John Boyd's OODA loop as an alternative to Kolb, *The International Journal of Management Education*, 20(3).

San Cristobal, J R, Carral, L, Diaz, E, Fraguela, J A and Iglesias, G, 2018. Complexity and Project Management: A General Overview, *Complexity*.

Stellman, A and Greene, J, 2014. *Learning Agile: Understanding Scrum, XP, Lean and Kanban*, 1st edition (O'Reilly Media Inc).

West, D, 2011. Water-Scrum-Fall Is The Reality Of Agile For Most Organizations Today, *For Application Development & Delivery Professionals* (Forrester).

Data augmentation for image-based rock fragment recognition using StyleGAN

Y Tang[1] and G Si[2]

1. PhD candidate, University of New South Wales, Sydney NSW 2052. Email: yudi.tang@unsw.edu.au
2. Senior Lecturer, University of New South Wales, Sydney NSW 2052. Email: g.si@unsw.edu.au

ABSTRACT

The analysis of rock fragment sizes plays a pivotal role in various stages of geotechnical and mining engineering. Traditional case-based methods often falter in addressing the variability in rock fragment images due to fluctuating geological conditions and imaging environments. To counter this challenge, AI-based models necessitate training on expansive and diverse data sets, encompassing a wide range of conditions and fragment types. However, the creation of such data sets is often hampered by financial and environmental constraints. This paper introduces a novel approach for rock fragment recognition, which leverages the power of AI for data augmentation, automated annotation and prediction. The methodology integrates three key components: Style-Based Generator Architecture for Generative Adversarial Networks (StyleGAN) for data augmentation, the Segment Anything Model (SAM) for automated annotation, and the multiscale version of you only look once (YOLO-MS) real-time instance segmentation model. The proposed method begins by training a new StyleGAN model using the original data set. It then delves into exploring the latent vectors of different rock fragment images to generate specific 'style representations'. These latent vectors form the foundational elements of each image in a high-dimensional space, encapsulating critical features such as size, shape, texture, and colour variations. The next step involves conducting quality checks on the generated images to ensure their realism and suitability as training data. Subsequently, the augmented image set is annotated using modified SAM module, followed by training the YOLO-MS real-time instance segmentation model. The performance of this model, trained on the augmented data set, is compared with a model trained on the original data set, particularly in terms of generalisation abilities in new scenarios. The results exhibit a significant enhancement in accuracy, robustness, and generalisability of the model trained on the augmented data set, underscoring the potential of StyleGAN as a powerful tool for data augmentation in geotechnical engineering image analysis.

INTRODUCTION

Rock fragments refer to the fragmented particles formed by the physical breakdown and separation of intact rock bodies (Steiglitz, 1988). The analysis of rock fragment gradation plays a crucial role in geological exploration, engineering construction, stability analysis, and other practices in geotechnical and mining engineering. However, traditional methods for obtaining the gradation have certain limitations. One approach heavily relies on visual observation, posing challenges to model accuracy, stability, and reliability. Another approach involves sieve analysis, which, while relatively accurate, demands significant time and labour costs (Tang, Wang and Si, 2024). With the continuous expansion of engineering scale and the increasing demand for real-time applications in various scenes, there is an urgent need for automated and high-precision methods to acquire rock fragment gradation.

Accurately extracting fragment regions or edges is a key step in obtaining particle size distribution. Traditional image processing algorithms are widely used to identify fragment pixels or detect fragment edges, but these algorithms perform well only when dealing with images that have clear semantics and reasonable contrast. Due to the complexity and variability of rock fragment images, differences in fragment size, shape, colour, lighting conditions, and data collection equipment in different scenes necessitate a significant amount of manual parameter adjustment, leading to algorithm instability. Some studies have combined traditional image processing with machine learning methods, but they rely on manual feature engineering. Other studies have explored semi-automated algorithms and human-machine interaction, which, although improving accuracy, introduce additional subjective manual tasks (Bamford, Esmaeili and Schoellig, 2021; Fan *et al*, 2022).

Since 2015, deep learning semantic segmentation and instance segmentation have been applied to fragment extraction or particle size analysis. These studies typically involve collecting images from specific scenes, manually annotating the data, and training supervised learning models to achieve efficient and accurate fragment recognition. However, these studies are usually case-based, meaning the models are only effective for the images encountered during training. When faced with new scenes, new images must be collected, manually annotated, and models trained in a time-consuming process, failing to meet the requirements for automated, real-time, and high-precision analysis (Vu *et al*, 2021).

Recently, the development of artificial intelligence (AI) applications has gradually entered the era of large models. Kirillov *et al* (2023) introduced the visual foundation model, Segment Anything Model (SAM). It utilises the largest segmentation data set in history, the Segment Anything 1-Billion Mask Data set (SA-1B), containing over 11 million images with a total of more than 1 billion masks. SAM's zero-shot performance is impressive, often comparable to or even superior to previous fully supervised results, demonstrating excellent adaptability to image variations. This paper proposes an adaptive framework for real-time recognition of fragments by integrating the zero-shot capability of large models and the real-time processing capability of small models. In particular, StyleGAN was used to enhance the data set.

METHODOLOGY

The flow chart of FragAdaptixAI is illustrated in Figure 1, comprising four main states:

1. Data collection state: Data is collected using methods such as smartphones, cameras, and three-dimensional model rendering. This approach gathers rock fragment images from various scenes, including laboratory settings, tunnel excavation, mining and construction sites, forming the foundation rock fragment image set.
2. Development state: The PCCS algorithm is initially employed to enhance contrast in the foundation rock fragment image set. Subsequently, SAM and a post-processing algorithm are utilised for image annotation, resulting in the foundation rock fragment data set. The RTMDet rock fragment recognition foundation model is trained on a server using this data set.
3. Fine-tuning state: When encountering a new case, the fine-tuning state is triggered. In this state, a small subset of images is extracted from the new case. After enhancement using the PCCS algorithm, SAM annotations, and post-processing, a fine-tuning data set is formed. This data set is used to fine-tune the foundation model obtained in the development state, producing the application model for the current case.
4. Application State: Images from the new case undergo PCCS processing and are input into the application model for initial rock fragment recognition results. Subsequently, through sub-image fusion and applying the OMS algorithm, the final recognition results are obtained.

This paper adds a StyleGAN enhancement to the foundation data set on the basis of FragAdaptixAI to achieve better results in foundation model training.

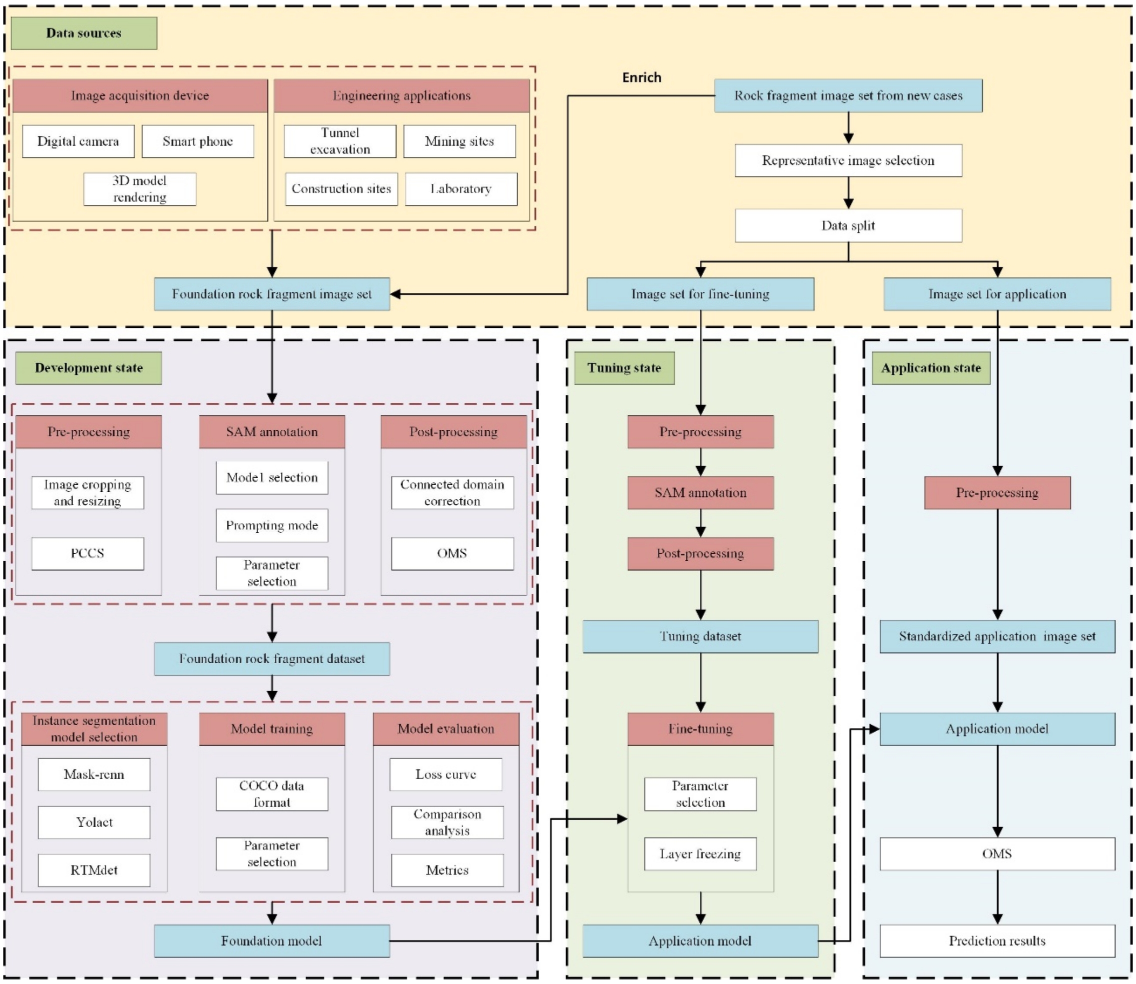


FIG 1 – Flow chart of FragAdaptixAI.

EXPERIMENT AND RESULT

We used 8000 original real images of size 512 × 512 in the StyleGAN training model. Figure 2 shows the fake images generated by the trained model, and it is difficult for the naked eye to distinguish between the fake and real images. These images were used to enhance the basic data set, and the basic model trained on the enhanced data set exhibited better generalisation performance compared to the model trained on the original data set. Evaluation metrics of different instance segmentation models can be found in Table 1. AP_i represents the AP value for the i-th class, and N is the total number of classes. mAP_l, mAP_m, and mAP_s are the mAP values corresponding to large, medium, and small-sized objects, respectively. From Table 1 we can see, the model performs better in recognising coarse (largre) particles.

FIG 2 – Generated images using StyleGAN.

TABLE 1
Evaluation metrics of different instance segmentation models.

Model	mAP_l	mAP_m	mAP_s	mAP
Mask R-CNN_r50	0.689	0.556	0.306	0.561
Mask R-CNN_r101	0.721	0.588	0.339	0.595
Yolact_r50	0.722	0.525	0.235	0.546
Yolact_r101	0.750	0.542	0.248	0.567
RTMDet-Ins-tiny	0.855	0.648	0.323	0.674

CONCLUSIONS

A combination of multiple technologies forms a framework for rock fragment recognition that is adaptive to various scenes. After the addition of images generated by StyleGAN, the bias in the feature distribution of the data set was effectively mitigated, thereby enhancing the effectiveness of the trained basic model.

REFERENCES

Bamford, T, Esmaeili, K and Schoellig, A P, 2021. A deep learning approach for rock fragmentation analysis, *Intnl Journal of Rock Mechanics and Mining Sciences*, 145:104839. https://doi.org/10.1016/j.ijrmms.2021.104839

Fan, H, Tian, Z, Xu, X, Sun, X, Ma, Y, Liu, H and Lu, H, 2022. Rockfill material segmentation and gradation calculation based on deep learning, *Case Studies in Construction Materials*, 17:e01216. https://doi.org/10.1016/j.cscm.2022.e01216

Kirillov, A, Mintun, E, Ravi, N, Mao, H, Rolland, C, Gustafson, L, Xiao, T, Whitehead, S, Berg, A C, Lo, W-Y, Dollár, P and Girshick, R, 2023. Segment Anything, in *2023 IEEE/CVF International Conference on Computer Vision (ICCV)*, pp 3992–4003. https://doi.org/10.1109/ICCV51070.2023.00371

Steiglitz, R D, 1988. Rock particles, fragments, in *General Geology*, pp 711–716 (Springer: Boston). https://doi.org/10.1007/0-387-30844-X_96

Tang, Y, Wang, Y and Si, G, 2024. Vision-based size distribution analysis of rock fragments using multi-modal deep learning and interactive annotation, *Automation in Construction*, 159:105276. https://doi.org/10.1016/j.autcon.2024.105276

Vu, T, Bao, T, Hoang, Q V, Drebenstedt, C, Hoa, P V and Thang, H H, 2021. Measuring blast fragmentation at Nui Phao open-pit mine, Vietnam using the Mask R-CNN deep learning model, *Mining Technology*, pp 1–12. https://doi.org/10.1080/25726668.2021.1944458

Automated characterisation of the dump materials

S Thiruchittampalam[1], B P Banerjee[2], N F Glenn[3] and S Raval[4]

1. PhD candidate, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: s.thiruchittampalam@unsw.edu.au
2. Lecturer, School of Surveying and Built Environment, University of Southern Queensland, Toowoomba Qld 4350. Email: bikram.banerjee@unisq.edu.au
3. Professor, Department of Geosciences, Boise State University, Boise ID, USA. Email: nancyglenn@boisestate.edu
4. Associate Professor, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: simit@unsw.edu.au

INTRODUCTION

The determination of shear strength parameters for the spoil material plays a crucial role in the assessment of a dump's stability; nevertheless, their evaluation necessitates laborious laboratory experiments. In order to address this issue, Simmons and McManus (2004) formulated a framework that serves as a foundation for categorising spoils according to their distinctive shear strength parameters based on observable and tactile characteristics. This framework, previously identified as the 'BHP Mitsubishi Alliance Coal (BMAC) Spoil Shear Strength Framework', is now recognised as the 'CoalSpoil' framework.

The spoil characterisation provided by the CoalSpoil framework offers benefits but is not without limitations. The examination of these attributes in the field is a time-consuming task that demands expertise. Subjectivity arises in the spoil characterisation when attributes straddle the line between two categories, such as delineating matrix-supported and framework-supported fabric structures. To enhance consistency in the spoil characterisation process, minimising human intervention is crucial to mitigate bias, classification errors, and safety risks. This study seeks to achieve this aim by introducing image-assisted and automated methods for spoil characterisation.

AUTOMATED CHARACTERISATION APPROACHES

This section explores three methodologies for spoil characterisation: pixel-level, object-level, and deep learning-based spoil characterisation.

Pixel level characterisation

The pixel-level characterisation of dump piles involved a multi-step process starting with collecting ground truth data to determining geotechnical parameters. Geotagged images were processed into a high-resolution, noise-filtered orthomosaic. Textural features were extracted, dimensionally reduced, and input into machine learning algorithms for optimal parameter determination. The study focused on lithology, fabric structure, and consistency due to drone data limitations, particularly for plasticity and particle size distribution.

Incorporating textural features improved accuracy of characterisation for three attributes. Lithology had the highest accuracy (82 per cent), while consistency/relative density and fabric structure had similar accuracy (77 per cent). Lithology's dependence on colour gave it an advantage in characterisation with optical data and textural features. K-nearest neighbour (kNN) excelled due to more training data and fewer features. Machine learning algorithms performed well with RGB and textural bands, suggesting further accuracy improvement by adding texture information (Thiruchittampalam *et al*, 2023).

Object level characterisation

Object level characterisation was employed to acquire a more comprehensive understanding of the delineated spoil pile and to mitigate the minor ambiguities observed in the pixel level categorisation. The technique involves the generation of orthomosaics using geotagged RGB and multispectral images captured by drones. The subsequent procedures consist of delineating the spoil pile boundary through a, a morphology-based segmentation technique applied to a digital surface model (DSM), followed by extraction and selection, and ultimately, the process of classification.

The object-based approach emphasises precise feature combinations for accurate characterisation with low computational demand (Thiruchittampalam *et al*, 2024). Fine kNN algorithm is most accurate for particle size and plasticity classification with RGB and multispectral data respectively. Wide neural network algorithm excels in relative density and fabric structure classification with RGB data. The ensemble algorithm achieves highest accuracy in BMAC category by combining features from RGB and multispectral data.

Close range image-based characterisation

The study also examined conventional and advanced CNN techniques for spoil characterisation using close range images.

ResNet18knn consistently outperforms in coal spoil attributes with high accuracies (above 95 per cent) and low deviations. ResNet18Ensemble shows lower accuracy for BMAC category, indicating the importance of tailored model selection. Bag of features, while accurate in some categories, require hand-crafted features and are more time-consuming than transfer learning approaches.

TEMPORAL PROFILE BUILDING AND STABILITY ANALYSIS

Based on the resultant classification from object level analysis, a block model of the dump was developed. Subsequently, a 3D stability analysis was performed, which provided a cohesive understanding of the spoil dump's stability.

Within the spectrum of stability assessments, the combination of General Limit Equilibrium and surface altering optimisation produced the most conservative factor of safety (Figure 1).

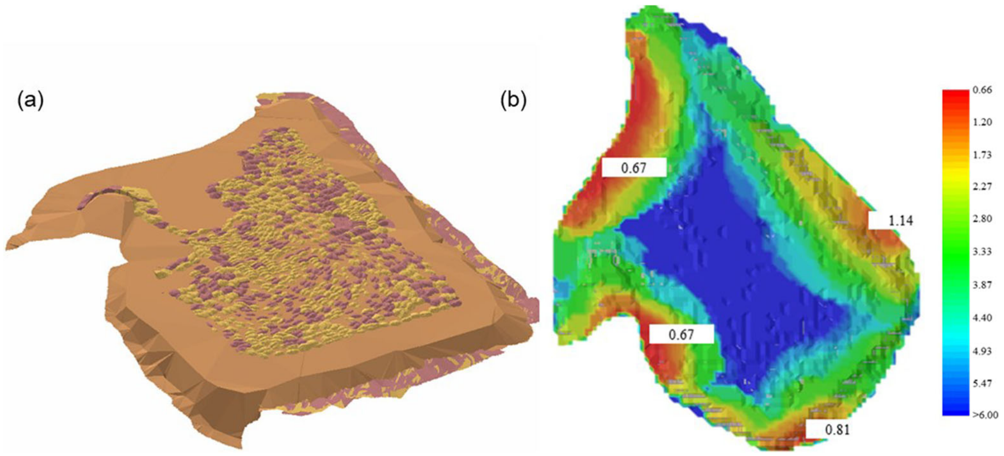


FIG 1 – (a) Outcome of 3D dump profiling, and (b) factor of safety map.

CONCLUSIONS

The study utilised drone and close-range imagery, along with machine learning, to characterise spoil piles. It highlighted the importance of feature extraction and the potential of multi-resolution image analysis for superior accuracy. It also showed that the performance of transfer learning excelled in spoil pile classification with an extensive data set. Furthermore, it demonstrated that the 3D profiling method, using drone data, enhanced slope stability analysis, thereby improving geotechnical assessments.

This study sets a strong foundation for automated characterisation of spoil piles using image analysis. Subsequent studies should consider employing sophisticated machine learning methods, particularly spatial data-focused deep learning models, to enhance classification accuracy and efficiency. Incorporating advanced sensors like hyperspectral imaging or LiDAR can improve data collection and classification accuracy. Monitoring spoil piles in real-time while mining is ongoing may support timely decision-making and adaptive management approaches.

ACKNOWLEDGEMENTS

This work was supported by the Australian coal industry's research [grant number C29048].

REFERENCES

Simmons, J V and McManus, D A, 2004. Shear strength framework for design of dumped spoil slopes for open pit coal mines, in Proceedings of the Advances in Geotechnical Engineering: The Skempton Conference, organised by the Institution of Civil Engineers and held at the Royal Geographical Society, pp 981–991 (Thomas Telford Publishing).

Thiruchittampalam, S, Banerjee, B P, Glenn, N F and Raval, S, 2024. Geotechnical characterisation of coal spoil piles using high-resolution optical and multispectral data: A machine learning approach, Engineering Geology, 329:107406.

Thiruchittampalam, S, Singh, S K, Banerjee, B P, Glenn, N F and Raval, S, 2023. Spoil characterisation using UAV-based optical remote sensing in coal mine dumps, International Journal of Coal Science and Technology, 10(1):65.

A practical model for LoRa propagation in underground mines

N Udugampola[1], X Ai[2], B Li[3] and A Seneviratne[4]

1. Postgraduate Researcher, UNSW, Sydney NSW 2052. Email: n.udugampola@unsw.edu.au
2. Postdoctoral Fellow, UNSW, Sydney NSW 2052. Email: x.ai@unsw.edu.au
3. Associate Professor, UNSW, Sydney NSW 2052. Email: binghao.li@unsw.edu.au
4. Professor, UNSW, Sydney NSW 2052. Email: a.seneviratne@unsw.edu.au

ABSTRACT

With the evolution of mining technology, wireless mesh networks using low-power, long-range technologies such as LoRa are increasingly utilised in underground mining operations. Efficient deployment of wireless nodes in such mesh networks necessitates understanding radio wave propagation behaviour in underground mines. While existing propagation models either remain theoretical or apply only to basic geometric shapes, we propose a practical approach to analyse radio wave propagation behaviour in underground mines using ray tracing simulations with reconstructed 3D models of targeted environments. Our method validated using a set of corridors as a substitute for underground mine environments, involves constructing a 3D model using SolidWorks from LiDAR scans of the environment and performing wireless transmission simulations using the MATLAB ray tracing toolkit. Our simulation model is also fine-tuned by calibrating the raytracing parameters based on real-world LoRa transmission experiments in the actual environment corresponding to the 3D model. This method offers a practical solution for optimising wireless node placement in underground mines, facilitating efficient network deployment while reducing the need for extensive physical testing of radio wave transmissions.

INTRODUCTION

Due to the long tunnel structures and highly constrained environments, wireless mesh networks based on Low Power Wide Area Network (LPWAN) technologies such as LoRa (Long Range) are more desirable for underground mines. When designing such a network for an underground mine, the efficient and precise deployment of wireless repeater nodes is crucial. This necessitates the characterisation of radio wave propagation behaviour in the underground mine. Although there is significant research on measurements and models of radio wave propagation in underground mines and tunnels, most of the existing propagation models are either theoretical models or empirical formulas analysing the basic shapes of mine tunnels. Zhou *et al* (2015) describe how radio frequency waves travel underground in a similar way to how they travel through dielectric waveguides. This is because the walls inside an underground mine act like the walls of a hollow waveguide, guiding the waves along the path. Developing a theoretical propagation model based on waveguide theory for an actual complex underground mine structure with multiple main tunnels, cross tunnels, and intersections may be very difficult, requiring an extensive number of complicated calculations. In this work, we introduce a method that can be practically utilised to estimate the optimal locations for the deployment of wireless nodes in a complex underground mine structure.

Utilising ray tracing simulations with 3D models to analyse radio wave propagation within mines and tunnels would be a more practical approach. Ray tracing is a method employed to trace the paths of electromagnetic rays as they traverse a 3D space, in a computer simulation. Qian *et al* (2022) have conducted ray-tracing simulations for a subway tunnel segment using a 3D model and compared the results with RF transmission experiments conducted in the actual subway tunnel, ultimately obtaining more similar results. Similarly, our method involves the construction of a 3D model of a mine structure using SolidWorks to study its radio wave propagation behaviour using the MATLAB ray tracing toolkit.

METHODOLOGY

Since we could not access an actual mine for this research, we utilised a set of corridors at the University of New South Wales, Sydney, as a substitute for an actual underground mine environment. An industrial LiDAR scanner (Leica C5) was employed to map the 3D information of these corridors. Multiple scans were conducted by positioning the LiDAR scanner at various locations within the corridors, and the 3D point clouds obtained from each scan were merged together using the software tool (Cyclone 2022) provided with the scanner. Figure 1 displays the merged point cloud of the set of corridors.

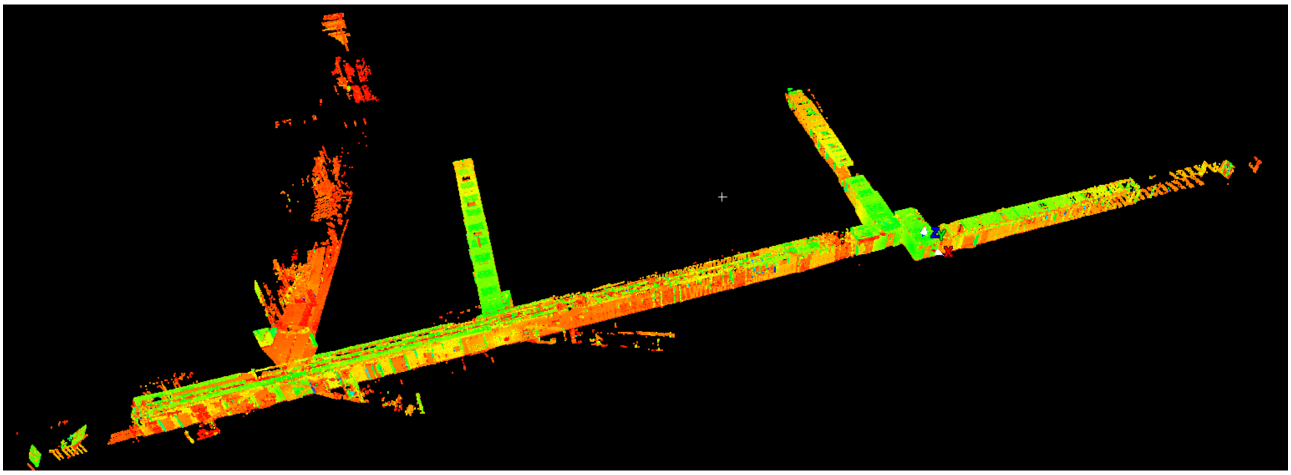


FIG 1 – Merged point cloud of the corridors.

This merged point cloud was then processed using MeshLab and SolidWorks to create a 3D model of the set of corridors. This 3D model could be imported to MATLAB to study the radio wave propagation using the MATLAB ray-tracing library. Figure 2 depicts a snapshot of a MATLAB ray-tracing simulation conducted with this model, positioning the RF transmitter and receiver at opposite ends of the corridors. Through this simulation, we could extract all propagation information, including path loss and signal strength at the receiver. MeshLab, SolidWorks, and MATLAB, utilised for this work, are all commercially available software packages.

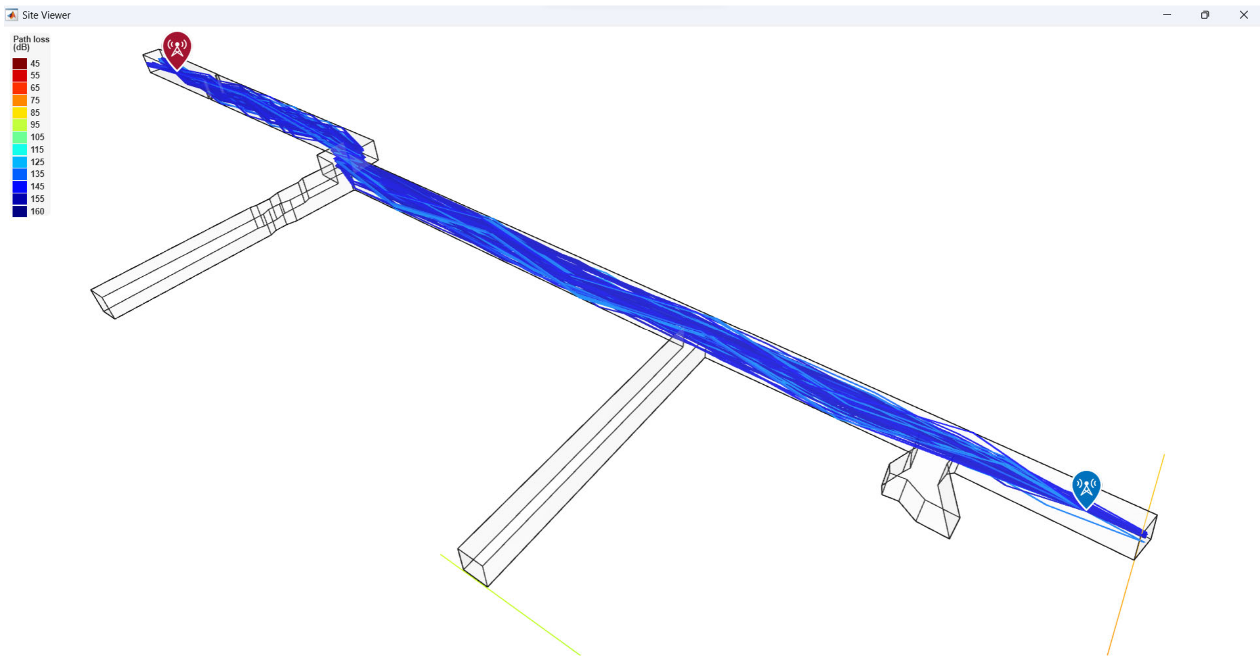


FIG 2 – MATLAB ray-trace site viewer.

We also conducted some actual LoRa transmission experiments in these corridors to create a data set of received signal strength indicator (RSSI) values based on different placements of the LoRa transmitter and receiver. Using the 3D model with the MATLAB ray-tracing toolkit, we could virtually recreate the same experiments done with hardware and create the same data set. The RSSI plots of the actual data and the data generated through ray tracing exhibit similar patterns, but there are offsets and variations. This is because, while the actual corridors and the point clouds contain a vast amount of detail, including objects, doors, and complex shapes on the walls, we opted to keep the final 3D model as simple as possible for the simplicity of our method, featuring only plain walls. To compensate for that, we calibrated the raytracing simulation by adjusting the numerical values of the reflection properties in the simulation to make the raytraced signal strength values closely align with the actual experimented values. Once the simulation model is calibrated with data from a significant number of on-site LoRa transmission experiments, it can be used for further simulation-based transmission experiments and mesh network planning, eliminating the need for extensive physical testing.

This method can be utilised to estimate the signal strengths when a random layout of an underground mine structure is provided because constructing a simple 3D model with basic dimensions suffices. Additionally, conducting a few transmission experiments inside the mine to extract experimental data is necessary to calibrate the ray-tracing simulation by fine-tuning its reflection properties which depend on the roughness and complexity of the walls inside the mine. After that ray-tracing simulations can be conducted by placing the transmitter and receiver at various locations within the mine structure using the 3D model. This allows for testing various transmitter and receiver placements without the need for physically testing each placement inside the mine.

CONCLUSIONS

In conclusion, the method presented offers a practical solution for estimating signal strengths within complex underground mine structures, eliminating the necessity for extensive physical testing. This approach not only streamlines the process of assessing transmitter and receiver placements but also lays the groundwork for optimising the deployment of wireless nodes within underground mines. This method can also be further improved as a software tool that can be utilised for the planning of underground mesh networks.

ACKNOWLEDGEMENTS

This work is supported by the Cooperative Research Centres Projects (CRC-P) Grants (No. CRCPXI0100216) under the project ‘Underground mine LoRa network for monitoring/control/ backup/rescue/robotics’.

REFERENCES

Qian, J, Wu, Y, Saleem, A and Zheng, G, 2022. Path Loss Model for 3.5 GHz and 5.6 GHz Bands in Cascaded Tunnel Environments, *Sensors*, 22(12):4524–4539.

Zhou, C, Plass, T, Jacksha, R and Waynert, J A, 2015. RF Propagation in Mines and Tunnels: Extensive measurements for vertically, horizontally, and cross-polarized signals in mines and tunnels, *IEEE Antennas and Propagation Magazine*, 57(4):88–102.

Application study of UAV technology in tailings pond monitoring

K Wang[1], Z Zhang[2] and T Zhao[3]

1. Lecturer, Shandong University of Science and Technology, Qingdao, 266590, China.
   Email: kwang@sdust.edu.cn
2. Master, Shandong University of Science and Technology, Qingdao, 266590, China.
   Email: zzsdust@163.com
3. Professor, Shandong University of Science and Technology, Qingdao, 266590, China.
   Email: ztbwh2001@163.com

ABSTRACT

Tailings pond safety monitoring is vital for preventing dam failures and ensuring environmental safety. Unmanned Aerial Vehicles (UAVs) can enhance tailings pond monitoring with flexible operational cycles and the ability to collect remote sensing data from inaccessible areas. While many mining operations have adopted UAVs for tailings pond management, their full potential in data acquisition and subsequent analytical processing remains largely untapped. This paper explores various case studies where UAVs have been utilised for monitoring key aspects of tailings ponds such as beach line indicators, dam displacement and erosion, slurry discharge processes, and tailings pond capacity. We also present examples where data derived from UAVs have been instrumental in slope stability analysis, seepage modelling, Tailings Dam Breach Analysis (TDBA), and risk prediction. By integrating UAV technology with traditional ground-based sensor techniques, this approach significantly enhances the precision and reliability of hazard prevention and management in tailings pond operations.

INTRODUCTION

There were signs before all tailings dam failures to date, in hindsight. Rigorous safety monitoring is globally recognised and implemented as an essential strategy for mitigating the risk of tailings dam failures, as well as for the safety management decision-making (Clarkson and Williams, 2020; Ruan *et al*, 2023; Rana *et al*, 2024). Throughout the life cycle stages of tailings pond site planning, construction, operation, closure, and remediation, safety monitoring of tailings ponds serves to pre-empt or minimise the occurrence of unforeseen accidents and their consequential impacts. Guidelines issued by governmental bodies or industry associations stipulate specific requirements for tailings pond safety monitoring.

Taking China as an example, it is notable that the country annually generates in over 1 billion tons of tailings and boasts ownership of, 4919 registered tailings ponds. Despite this substantial volume, China has demonstrated marked advancements in the prevention of dam failures over the last decade. Regulations in China mandate the construction of monitoring systems for various parameters including dam displacement, phreatic line depth, beach width, beach slope, precipitation, water level, displacement of geological landslide near the tailings pond area, and video surveillance of important areas. Among there, the monitoring of beach line indicators (BLIs), which include the beach width and slope index between the embankment crest and the decant pond, has received significant attention from researchers and industry. It is specified that the measurement section for the beach width should be oriented perpendicular to the dam axis, and the minimum measured value should be used as the representative beach width. A wider beach typically indicates a lower phreatic line and a higher safety factor. In China, tailings ponds are categorised into five grades based on their capacity and dam height, with regulatory minimum beach widths set at 40 m, 50 m, 70 m, 100 m, and 150 m, respectively. The beach slope is integral to the dispersion and sedimentation of tailings, the efficiency of consolidation drainage, and the operations of flood discharge systems (Jewell, 2012; Li, 2015). These BLIs serve as proxies for the phreatic line depth and the flood prevention capabilities. They are influenced by various factors, including the constant changing tailings pond geometry, rainfall, wind, and tailings slurry fluidity (Justo *et al*, 2019). Insufficient control over BLIs, particularly inadequate beach width, presents a significant risk of heightened water levels and overtopping or seepage dam failures. The increasing prevalence of fine particle tailings in the industry poses additional challenges in terms of permeability and dam stability (Hudson-Edwards, 2016), underscoring the importance of BLIs monitoring.

Unmanned Aerial Vehicles (UAVs) are increasingly utilised in mining industry due to their portability, high precision, and cost-effectiveness. These attributes render UAVs especially beneficial for capturing high-definition imagery of tailings ponds, areas often characterised by challenging terrain, inaccessible areas and minimal vegetation. Furthermore, UAVs enable the precise acquisition of detailed surface elevations through advanced photogrammetry techniques, demonstrating substantial potential for applications within the tailings pond monitoring. However, the current deployment is predominantly limited to basic UAVs video inspections of environment. A notable deficiency exists in the development of data processing methodologies that align with the monitoring indicators required by regulatory standards. Meanwhile, it is crucial to timely evaluate the safety of tailings ponds based on monitoring data to ensure their safe operation. The prerequisite for accurately assessing the safety posture is to ensure the reliability and comprehensiveness of the monitoring data.

Therefore, this study proposes an innovative approach that combines UAV photogrammetry (UAVP) with convolutional neural networks (CNNs) to effectively extract the critical monitoring indicators, providing input parameters and precise geometric model to enhance numerical simulations of dam stability and seepage evaluation. Several case studies were carried out to demonstrate the efficacies of the proposed approaches. Designed to substantially enhance safety monitoring and risk assessment practices within tailings pond management, the approaches aim to bridge the gap between current capabilities and regulatory requirements, thereby improving the reliability and efficiency of tailings management.

MONITORING OF TAILINGS POND DEPOSITED BEACH LINE INDICATORS

Traditional beach line indicators monitoring methods

The monitoring of beach line indicators (BLIs), which include the beach width and slope index between the embankment crest and the decant pond, has received significant attention from researchers and industry. The BLIs is closely related to the phreatic line depth and the flood prevention capabilities, which is an important parameter for monitoring the safety of tailing ponds. Various methodologies are employed for monitoring beach line indicators, as illustrated in Figure 1. The visual identification method (Figure 1a) utilises signs placed at regular intervals along the beach (eg every 50 m or 100 m). It is prone to inaccuracies and can only provide specific cross-section data. Thus the comprehensive status of the beach area cannot be captured. Advanced adaptations of this method by Hu *et al* (2013) involve calibrating the camera's inherent parameters to enhance measurement accuracy, while Yang *et al* (2019) employ the Mask R-CNN algorithm for real-time and automated video analysis. The radar level gauge method (Figure 1b) estimates the beach slope by using preset elevation measuring points and spacing between gauges to calculate the slope θ. Although providing detailed data, this method is resource-intensive, requiring frequent recalibration to prevent gauge submersion due to accumulating tailings, thus increasing operational costs. The laser ranging method (Figure 1c) involves a laser device at the dam crest that measures the irradiated laser beam angle α and the distance l to the decant pond boundary. Then the beach slope θ and width w can be calculated based on the height difference Δh between the laser beam h_{LB} and measured decant pond water level h_{decant}. This method is restricted by the laser range and also typically captures only a single cross-sectional view, which may not represent the shortest beach width. The seepage back-calculation method (Figure 1d) involves placing piezometers beneath the beach section to determine the phreatic line depths. Subsequently, the relationship $l_{beach} = F(h_{decant})$ is employed to derive both the beach slope θ and width w from the measured beach crest height h_{BC} and decant pond water level h_{decant}. This method primarily reflects BLIs along the phreatic line, only providing a single cross-sectional view. Lastly, the constant slope estimation method assumes a uniform beach slope to approximate BLIs using measured elevations at the beach crest and decant pond water level. While straightforward and applicable in smaller ponds, this assumption can significantly distort the accuracy of the actual beach width observed, leading to potential miscalculations in safety assessments.

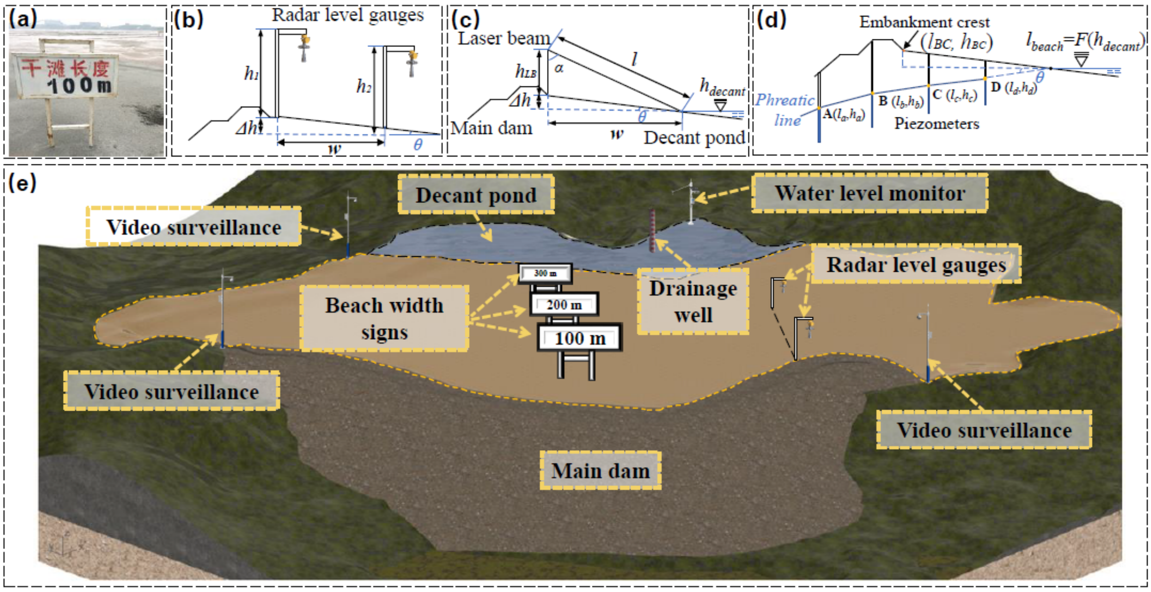


FIG 1 – Diagram illustrating common BLIs monitoring methods. (a) Equidistant beach width signs placed along the beach section used for the visual identification method. (b) The radar level gauge method, illustrating its set-up and data collection technique. (c) The laser ranging method, illustrating the device set-up at the dam crest, the measurement of the irradiated laser beam angle α and the distance l to the decant pond boundary. (d) The seepage back-calculation method, illustrating the placement of piezometers and the principle for calculating the BLIs. (e) Arrangement layout of the tailings pond BLIs monitoring devices.

Methodology for BLIs observation using UAV photogrammetry

The integration of UAV photogrammetry with Convolutional Neural Networks (CNNs) enables intelligent identification of the deposited beach area and the overlying decant pond area from orthophoto images. Specifically, the optimised YOLACT model (Figure 2) and Deeplabv3+ model (Figure 3) are employed for recognising the deposited beach area and the overlying decant pond area, respectively. Calculation of the beach width involves extracting the water level line and the top line of the beach, combined with raster calculation methods. The beach slope is determined by extracting elevation data along profile lines from the DSM and performing subsequent calculations.

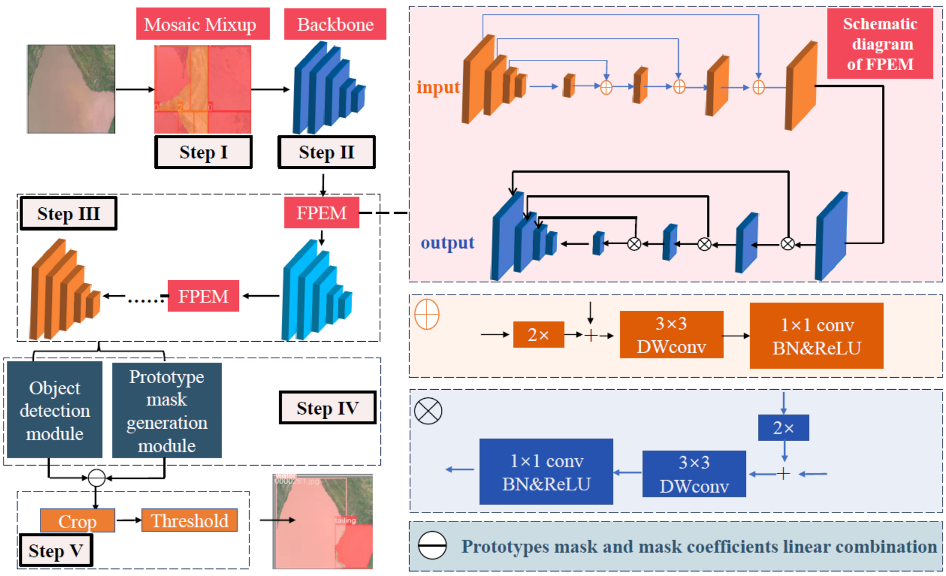


FIG 2 – Optimised YOLACT model workflow. Here, '+' denotes element-wise addition, '2×' indicates twice linear upsampling, 'DWconv' stands for depthwise convolution, and 'BN' refers to batch normalisation.

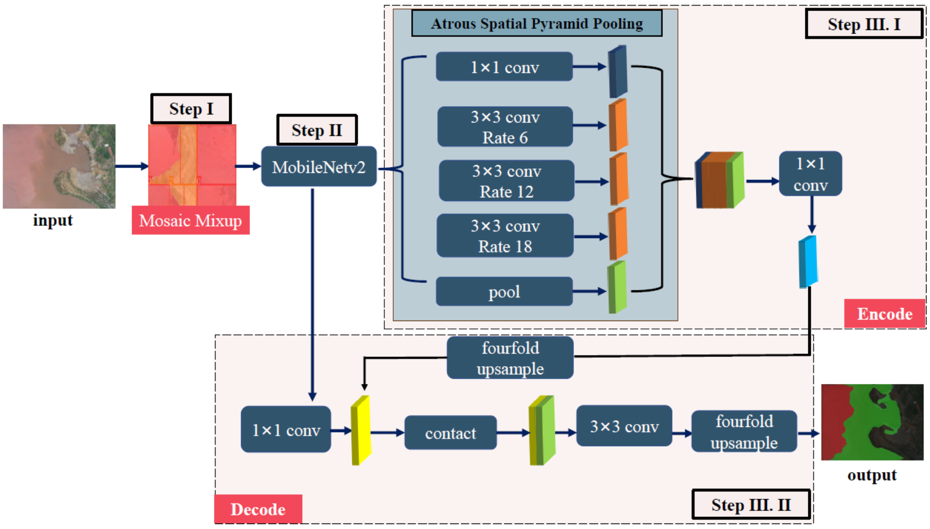


FIG 3 – Optimised DeepLabV3+ model workflow.

The research procedure is as follows:

1. UAV Survey

   DOM and DSM of the tailings pond and its surrounding environment are generated from UAV surveys and photogrammetry processing.

2. Data set Preparation

   A data set comprising 600 images of tailings ponds is assembled. using ArcGIS 10.2 software. Then the data set is expanded to 6000 images using the Mosaic Mixup data augmentation module. These images are meticulously annotated using precise tools to ensure accurate labelling. The data set is divided into training (90 per cent) and testing (10 per cent) subsets to facilitate the development and validation of CNN models.

3. Model Training and Evaluation

   The optimised YOLACT and DeepLabV3+ models are trained separately with the prepared data set to extract beach and water areas. The performance of these models is evaluated and compared against manual annotated results to ascertain the more effective model.

4. Beach Boundary Line Extraction

   Deploy the identified superior CNN model to extract the boundary line between the beach and decant pond from the UAVP-generated DOM.

5. Beach Width Measurement

   The distance between the water boundary and the embankment crest is determined by connected component extraction using MATLAB software. It is then converted into actual measurement by scaling with the grid pixel size to determine the shortest beach width.

6. Beach Slope Measurement

   Beach slopes are determined based on the elevation changes observed in multiple profiles drawn on the DSM. The average beach slope is then calculated.

Results

Taking a gold tailing pond in East China (Figure 4a) as an example, the DJI Matrice 350 RTK quadcopter drone equipped with a Zenmuse P1 full-frame camera was used in this study. The surveying was executed with flight routes arranged in a ‘cross’ pattern to optimise coverage. The planned heading and lateral overlaps were 70 per cent and 80 per cent, respectively, at a flight altitude of 120 m, achieving a Ground Sampling Distance (GSD) of 1.5 cm/pixel. A total of, 1739 images were collected. These images were then processed to produce high-resolution DOM and DSM, as presented in Figure 4.

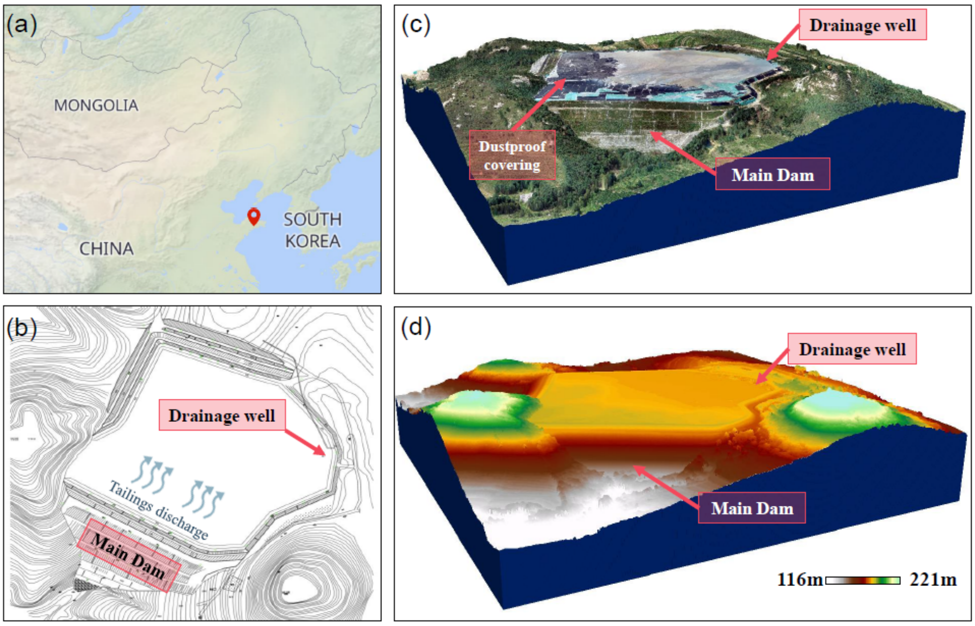


FIG 4 – Information and UAV aerial survey results of the tailings pond in the case study. (a) Geographical location. (b) Structural composition. (c) UAV aerial survey Digital Orthophoto Map (DOM) texture. (d) Digital Surface Model (DSM) topographic results.

Model performance and beach width calculation

The optimised DeepLabV3+ model achieved an MIoU of 63.41 per cent and an mPA of 67.3 per cent. The optimised YOLACT model demonstrates enhanced performance, achieving an MIoU of 72.63 per cent and an mPA of 76.2 per cent. Utilising the optimised YOLACT model, the contours delineating the beach interface and the boundary edge of the decant pond are extracted from the UAVP-generated DOM, as shown in Figures 5 and 6.

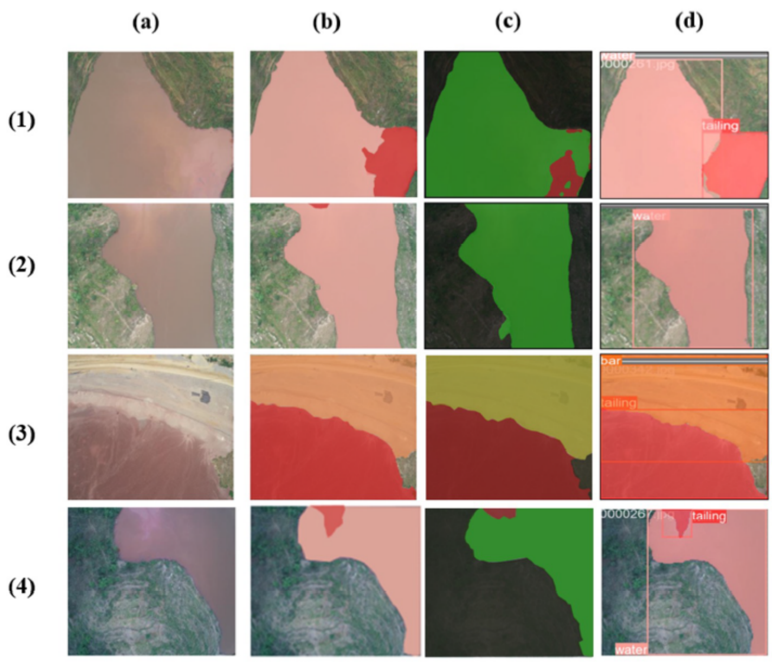


FIG 5 – Comparison of automated recognition results. (a1~a4) Original images. (b1~b4) Manually annotated results. (c1~c4) Recognition results of optimised DeepLabV3+. (d1~d4) Recognition results of optimised YOLACT.

FIG 6 – The extracted contours delineating the beach interface and the boundary edge of the decant pond using the optimised YOLACT model.

The methodology for automatically determining the minimum beach width involves a series of raster computations. Initially, the high-resolution orthophoto is aligned with the DSM, restoring the positional accuracy lost during the image recognition phase. This aligned image is then subjected to binary classification. Areas representing waterlines and dam lines are assigned a binary value of 0 (black), while all other regions are set to 1 (white). Connected component analysis is applied to identify and categorise the grids associated with the waterlines and dam lines. Through iterative analysis of these categories, the minimum distance between these features is calculated to be 127.53 m. Recording the Z-coordinates of the end points at this distance, the shortest linear distance is then scaled by the pixel size of 1.5. By incorporating this calculation with the elevation data, the spatial shortest beach width is computed to be 191.31 m.

Beach slope calculation

Observations of the beach slope must be arranged with at least two sections every 100 m, and the spacing between measurement points should not exceed 10～20 m, according to the current Chinese 'Technical Specifications for Safety Monitoring of Tailings Ponds' (AQ2020−2010). UAVP-generated DSM can be used to extract elevation measurements for any section, offering a more efficient coverage compared to the observational methods previously discussed. With the main dam length measured at 270 m, six sections are established in accordance with the specifications, each approximately 45 m apart, as shown in Figure 7a. These sections are then aligned with the DSM to extract 3D coordinates of line segments for subsequent slope calculations. The beach slope variations from section I to section VI, plotted in Figure 7b～7g, demonstrate average slopes of 1.5 per cent, 1.4 per cent, 1.2 per cent, 1.5 per cent, 1.3 per cent, and 1.6 per cent respectively. Consequently, the calculated average beach slope for the tailings pond is determined to be 1.42 per cent.

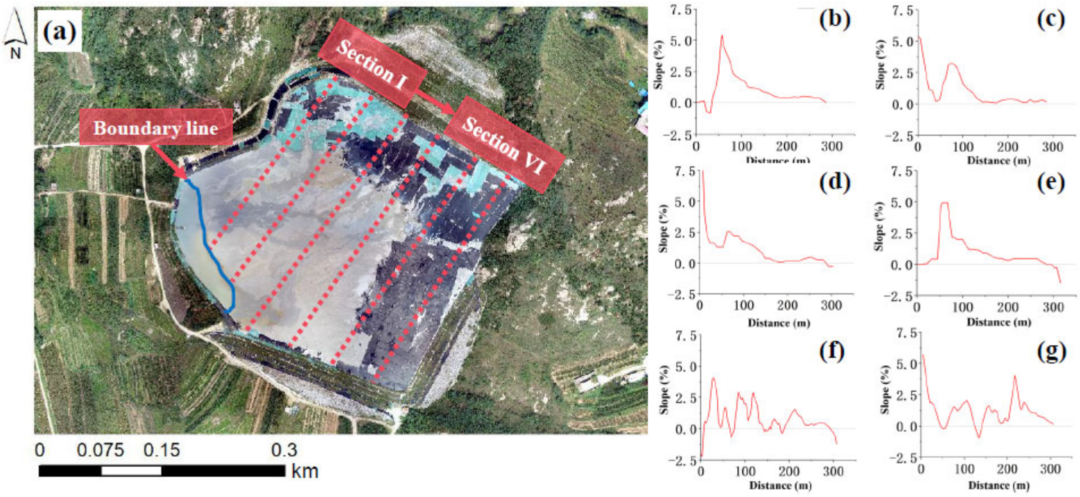


FIG 7 – Calculation of deposited beach slope.

MONITORING OF DAM DISPLACEMENTS AND SURFACE EROSION

Dam displacement monitoring

Monitoring deformation of tailings dams provides crucial data reflecting dam safety. UAV-based monitoring utilises computer vision technology for acquiring and reconstructing three-dimensional geographic information data of tailings storage areas. This process involves two phases: distance calculation processing using point cloud data from different time points to monitor surface and overall deformation, and analyse detailed changes.

An illustrative example from an iron ore mine tailings pond in East China (Yang *et al*, 2021) demonstrates this approach. Following UAV aerial survey data collection, point cloud data of cement piles on the dam surface were aligned to assess deformation based on changes in point cloud distances. Figure 8c depicts the surface deformation monitoring map. In June, the mine repaired dam slopes and cleared weeds in preparation for the rainy season. The sub-dam platform and slope surface were newly layered with loose soil. By October, approximately four months later, the newly laid soil had undergone substantial volume contraction and consolidation, albeit with incomplete solidification from the repairs in June. After the rainy season's scouring in October, new gullies had essentially re-formed in their original locations due to the low consolidation of the overlaying soil.

Figure 8a provides an enlarged view of area E, indicating a tendency towards landslides with horizontal cracks ranging from 1–4 mm and vertical cracks of 1–3 m near the slope shoulder. By October, a landslide had occurred after the rainy season, as depicted in Figure 8b. Due to insufficient timely repairs, the adjacent area had significantly widened and deepened by October. Measurements showed a maximum widening of 0.56 m and a maximum deepening of approximately 0.27 m compared to June.

This enhanced monitoring approach provides critical insights into dam stability and informs timely maintenance and mitigation efforts.

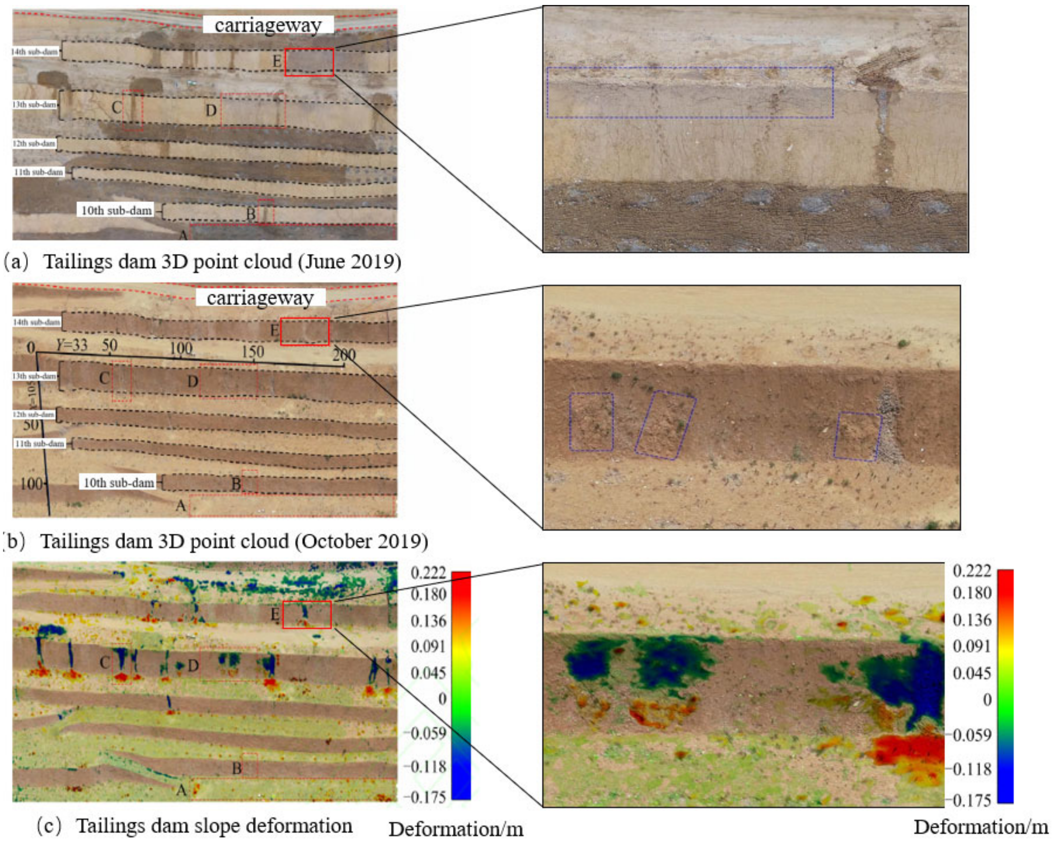


FIG 8 – Example map of surface deformation monitoring of tailings dam body (Yang *et al*, 2021).

Mine GNSS monitoring data indicate uniform settlement of the tailings dam body slope within 0.026 m. Figure 9 illustrates that environmental factors affect the soil body slope, leading to deformations such as gullies and landslides, which are not captured by GNSS due to its point-based observations. In contrast, UAV photogrammetry-based deformation monitoring data show significant profile changes, especially evident in the X = 105 profile, surpassing the monitoring capabilities of GNSS. UAV photogrammetry data better capture abnormal deformations like gullies and landslides along the profile. This comparison highlights the complementary strengths of UAV photogrammetry in detecting and monitoring dynamic surface changes that GNSS may overlook.

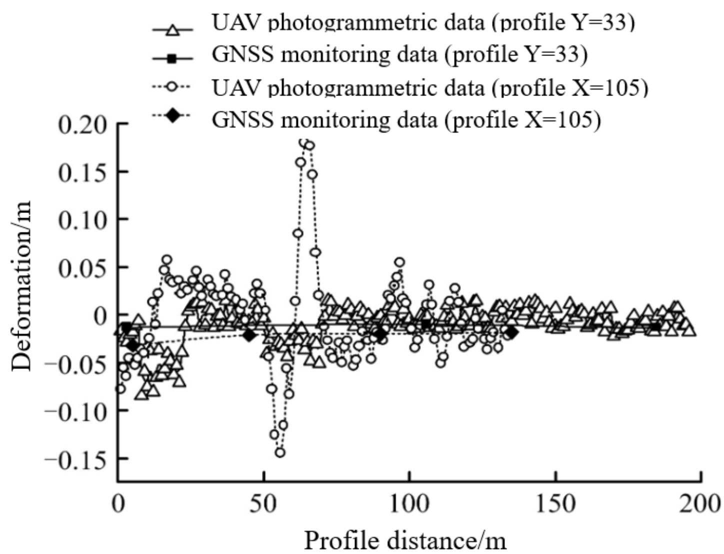


FIG 9 – Comparison of UAV monitoring with GNSS monitoring (Yang *et al*, 2021).

Surface erosion monitoring

Rainfall and surface seepage are primary causes of erosion on tailings dams. Unmanaged erosion poses significant risks. UAVs, leveraging their broad field of view and high efficiency, coupled with CNN models, enable automated monitoring of surface erosion. This approach enhances the safety management of tailings ponds by promptly detecting and addressing erosion, thereby mitigating potential hazards. Figure 10 illustrates the erosion phenomenon on a dam slope of the aforementioned iron ore tailings pond, clearly captured by UAVs, providing effective early warning messages for the mining operators.

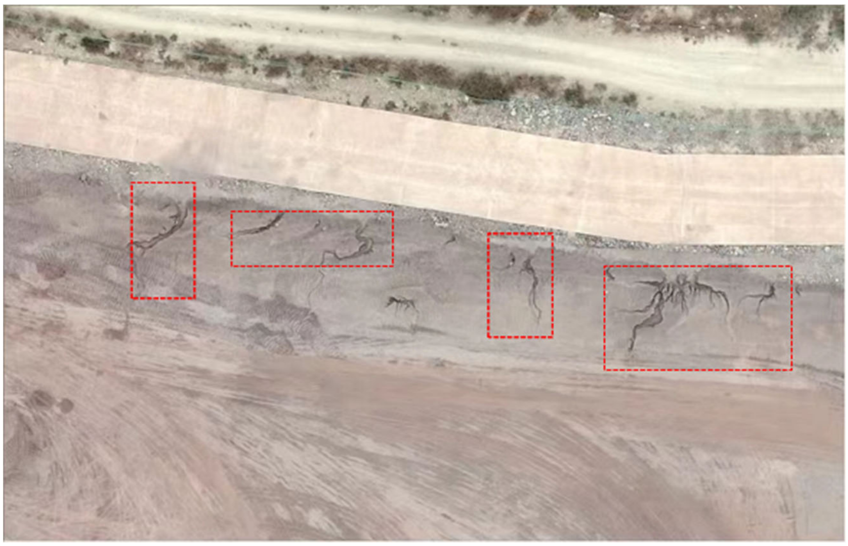


FIG 10 – Erosion on the dam surface captured by UAVs.

MONITORING OF SLURRY DISCHARGE PROCESS AND CAPACITY CHANGES

Monitoring of slurry discharge process

Employing an Unmanned Aerial Vehicle (UAV) equipped with an infrared thermal imaging sensor facilitates the monitoring of slurry flow trajectories. This method enables a comprehensive understanding of slurry flow dynamics, offering crucial data for optimising the positioning of the slurry discharge pipe. Timely adjustments in tailings flow within the pond area are essential to prevent the formation of reverse slopes. The UAV's thermal infrared sensor tracks the trend of tailings slurry flow, as depicted in Figure 11. It has been observed that the slurry discharged from the pipe exhibits the higher temperature, which gradually decreases with distance travelled.

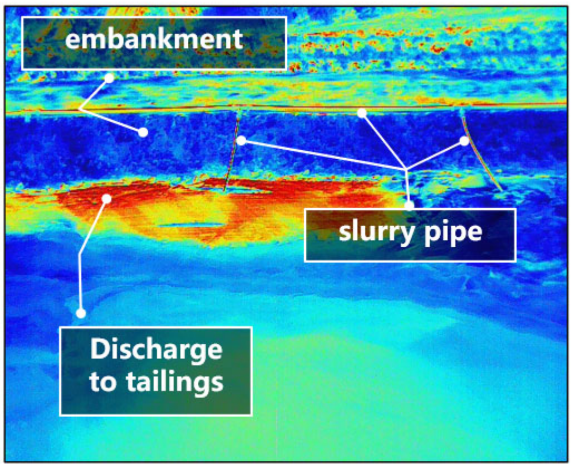


FIG 11 – Slurry discharge process monitoring map.

Tailings pond capacity monitoring

ArcGIS 10.2 is utilised alongside Digital Surface Model (DSM) data to monitor the remaining capacity of tailings ponds. Analysis of multi-period DSM data enables assessment and prediction of capacity changes, crucial for dam construction planning.

The edge line of the tailings pond identified from orthophotos is recognised using a CNN model and integrated with the DSM to obtain 3D coordinates. The DSM model is cropped to the pond area to calculate its capacity. Using a conditional function, raster elevation values greater than the overflow elevation of tailings slurry are adjusted to this elevation. Each grid's elevation in the DSM model is subtracted from the overflow elevation to derive the remaining capacity DSM model. Volume for each image is calculated based on its size and elevation, then superimposed to yield the final capacity result. Taking an iron ore tailings pond in East China as an example, UAV and CNN calculations show that during the November, 2023 aerial survey, the tailings storage area was 690 762 m^2 with a remaining capacity of 3 328 709 m^3. In December 2023, the surveyed area expanded to 694 341 m^2 with a remaining capacity reduced to 2 853 186 m^3. The theoretical daily disposal volume during this period is estimated at 27 573 m^3. This method effectively aligns with actual capacity calculations compared to traditional manual measurements, as conventional methods of quantifying pipeline flow cannot account for wastewater content. In contrast, the UAV observation method proposed in this study captures genuine capacity changes post-dehydration sediment consolidation.

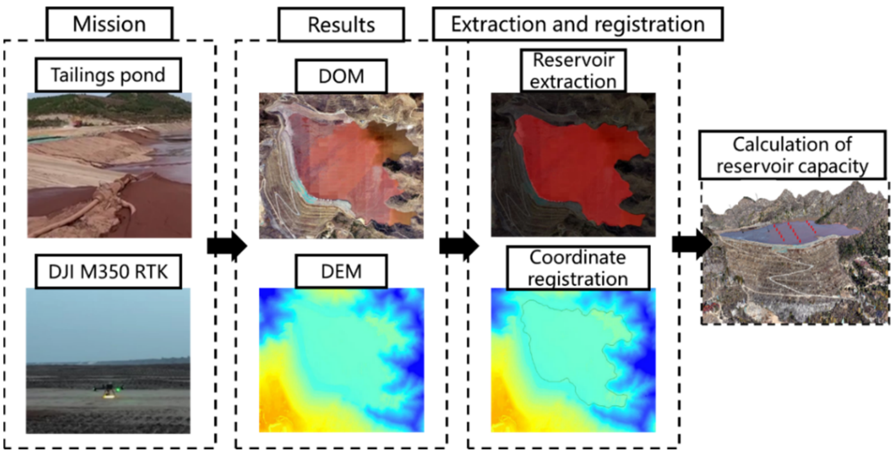


FIG 12 – Schematic diagram of the capacity calculation.

UAV-GENERATED DATA FOR SLOPE STABILITY AND SEEPAGE ANALYSIS

UAV-generated data for slope stability analysis

The dam stability coefficient and phreatic line are critical indicators reflecting dam stability. Utilising UAV photogrammetry and the optimised YOLACT CNN model, the water level identified aids in dam stability and seepage analysis, providing a more accurate assessment of site stability and seepage conditions. The 3D model closely represents the actual dam body, reflecting its stability and seepage characteristics, accounting for variations from the design model due to construction and natural factors.

Taking the gold tailings pond in East China (Figure 4) as an example, the current elevation of the tailings pond is determined using DSM data. The decant pond boundary line and its water level are determined through UAV surveys and CNN model identification. Physical property parameters of rocks and soils in each layer of the tailings pond are detailed in Table 1.

TABLE 1
Parameters of physical and mechanical properties of each rock and soil layer.

Geotechnical name		Heaviness γ (KN/m^3)	Cohesion C (kPa)	Angle of internal friction Φ (°)	Permeability coefficient K (m/s)
Infrastructural	Strongly weathered granite	22	0	41	/
Initial dam	Crushed rock pile dam	21	0	36	1.0×10^{-3}
Drift dam	Crushed earth and rock dam	20.5	1	37	3.5×10^{-5}
Tailings layer	Tailings sand	19.2	6.4	30	5.5×10^{-7}
	Tailings powder soil	18.5	13.7	26.4	5.09×10^{-7}

Based on the simplified 2D model, pseudo 3D model (P-3D) and real 3D model (R-3D) derived from UAV photogrammetry, the slope anti-sliding safety coefficients of the current tailings pond were calculated using the commonly used Bishop and SRM method. The results of the tailings dam safety coefficients are presented in Figure 13, indicating dam stability coefficients of 2.096, 3.10, 3.86 and 4.00.

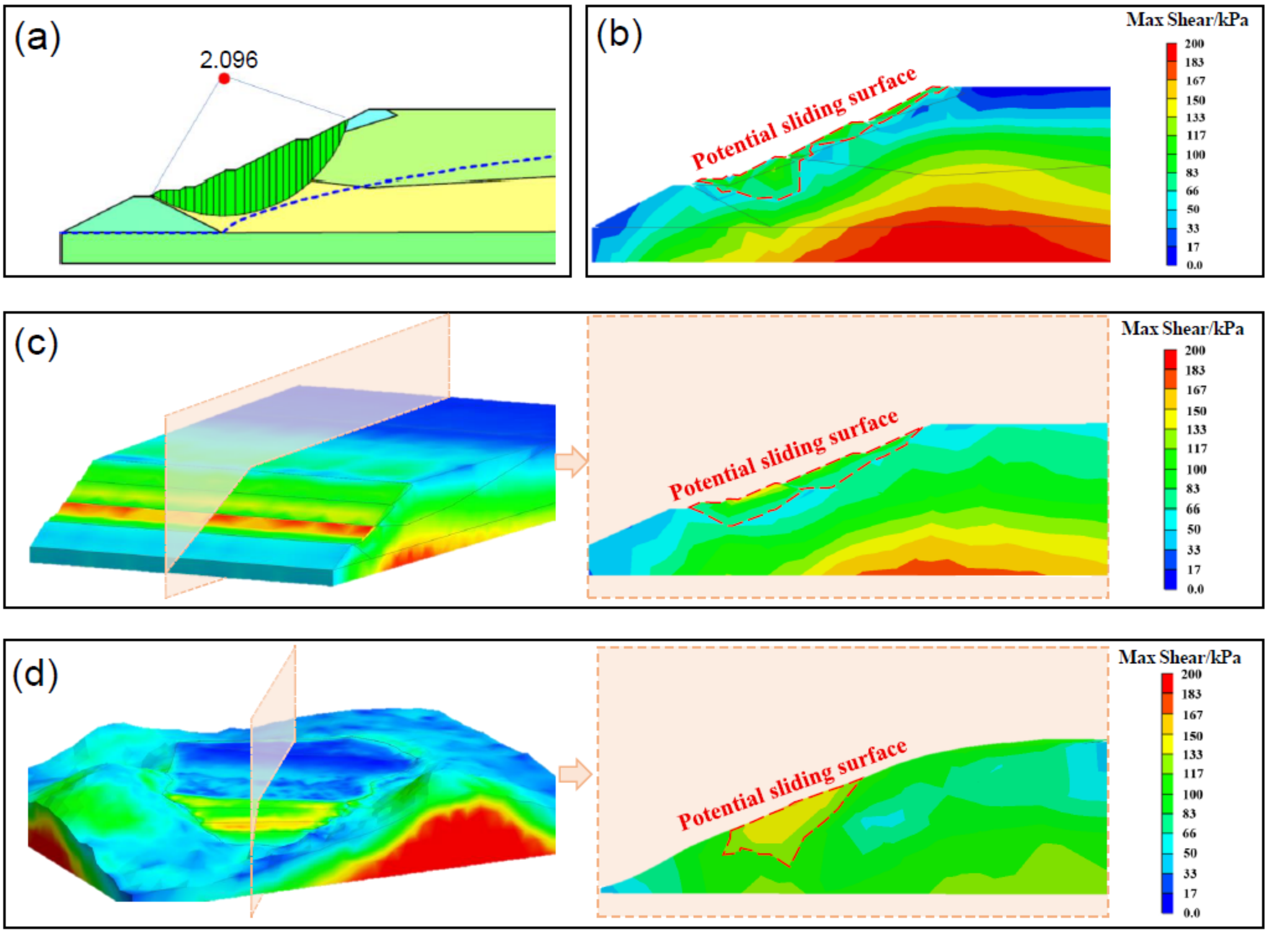


FIG 13 – Comparison of models and slope stability analysis results.

The dam stability coefficient, determined using 2D simplified Bishop method is 2.096 (Figure 13a), surpassing the safety threshold mandated by current Chinese regulations, which stipulate a minimum safety factor of 1.25 for the fourth-class tailings dams in the case study. The potential sliding surface is identified within the central segment of the dam embankment, spanning an area of 228.1 m^2. The dam stability coefficient determined using the 2D SRM method is 3.10 (Figure 13b), indicating a 47.9 per cent increase compared to the Bishop method. The identified potential sliding surface extends from the embankment crest to the initial dam crest, primarily located in the lower central portion, encompassing an area of 226.4 m^2. The stability coefficient calculated using the P-3D SRM method is 3.86 (Figure 13c), demonstrating a 24.5 per cent increase compared to the 2D SRM method. The peak shear stress is distributed similar to the 2D SRM calculation, covering an area of 249.1 m^2, with stress distribution from 83 to 200 kPa. The stability coefficient obtained from the R-3D SRM method is 4.00. Analysis of shear stress distribution along a profile perpendicular to the main dam axis reveals the primary potential sliding surface situated at the embankment's centre, with an associated potential sliding area of 230.6 m^2. Shear stress on the potential sliding surface varies from 117 to 183 kPa, suggesting correlation with factors such as dam geometry, beach width, and water level conditions.

The real 3D model depicts the tailings dam body's geometry as an inverted trapezoid, with significant shear stress concentration observed at the trapezoidal long base's midpoint. In contrast, shear stress on the lateral sides, corresponding to the dam abutments, are comparatively lower. This disparity underscores the necessity of employing real 3D modelling techniques in dam safety coefficient calculations. As Wu *et al* (2020, 2023) demonstrated in the field of landslide research, the three-dimensional geometric shape of the dam body has a significant impact on the stability analysis results. Furthermore, tailings dams, often constructed in valleys, may have their stability analysis results influenced by the surrounding valley geometry (Chugh, 2014). These factors underscore the importance of conducting 3D dam stability analysis based on UAV aerial surveys.

The simplified Bishop method solely accounts for inter-slice normal forces, fulfilling vertical force balance and overall moment equilibrium, its computational process is relatively straightforward, thus making it widely applicable in engineering practices (Kumar, Choudhary and Burman, 2023). In contrast, the SRM method comprehensively addresses static equilibrium, strain compatibility, and the nonlinear stress-strain relationship of soil masses. Its application extends to calculating dams with complex topography and geology, unrestricted by dam geometry, boundary conditions, or material heterogeneity. When determining safety factors, there is no need to assume the potential sliding surface or perform slice divisions. Instead, the program automatically determines the sliding surface, locating sliding failure within regions characterised by shear strain increments, plastic strains, or abrupt displacement changes (Xu and Wang, 2015).

The 2D computational approach demonstrates significant efficiency, facilitating seamless integration with online safety monitoring systems by incorporating variables such as water level monitoring, thus enabling real-time dynamic assessment of tailings dam stability coefficients. It is crucial to acknowledge that 2D methods may potentially underestimate actual dam stability and is most suitable for dams characterised by regular geometries and uniform geological conditions (Ho, 2014). The P-3D method partially incorporates 3D effects and is particularly suitable for stability analyses characterised by significant length-to-height ratios.

Despite the prolonged duration required for establishing 3D stability calculations using SRM, the computational duration remains about 10 mins, the time investment is fully justifiable for engineering design assessments or validating alterations at this magnitude. Furthermore, the rapid advancement of high-performance computing devices is anticipated to mitigate any adverse effects on computational efficiency associated with 3D calculations.

Higher stability coefficients could mitigate regulatory pressures on mining companies while reducing the margin of error in safety evaluation. Regulatory authorities should strive to balance setting minimum stability coefficients that ensure adequate error margins with promoting sustainable mining approaches. Excessively stringent regulations may force companies to over-invest in dam construction, heightening construction difficulties and unsustainable costs, which could detract from investments in safety operations, monitoring system maintenance, and environmental protection, ultimately undermining the overall safety management of tailings ponds.

UAV-generated data for seepage analysis

The phreatic line serves as a crucial indicator for the stability of tailings ponds. Using the gold tailings pond in East China (Figure 4) as a case study, three-dimensional seepage calculations and predictions were conducted under simulated rainfall conditions, specifically with a 24-hour rainfall of 50 mm. The seepage calculation model utilises the real three-dimensional model of the tailings pond obtained via UAV photogrammetry. Initial water levels are set based on the minimum width of the deposited beach and the range of UAV photogrammetric water levels, with comparisons depicted in Figure 14a and 14b.

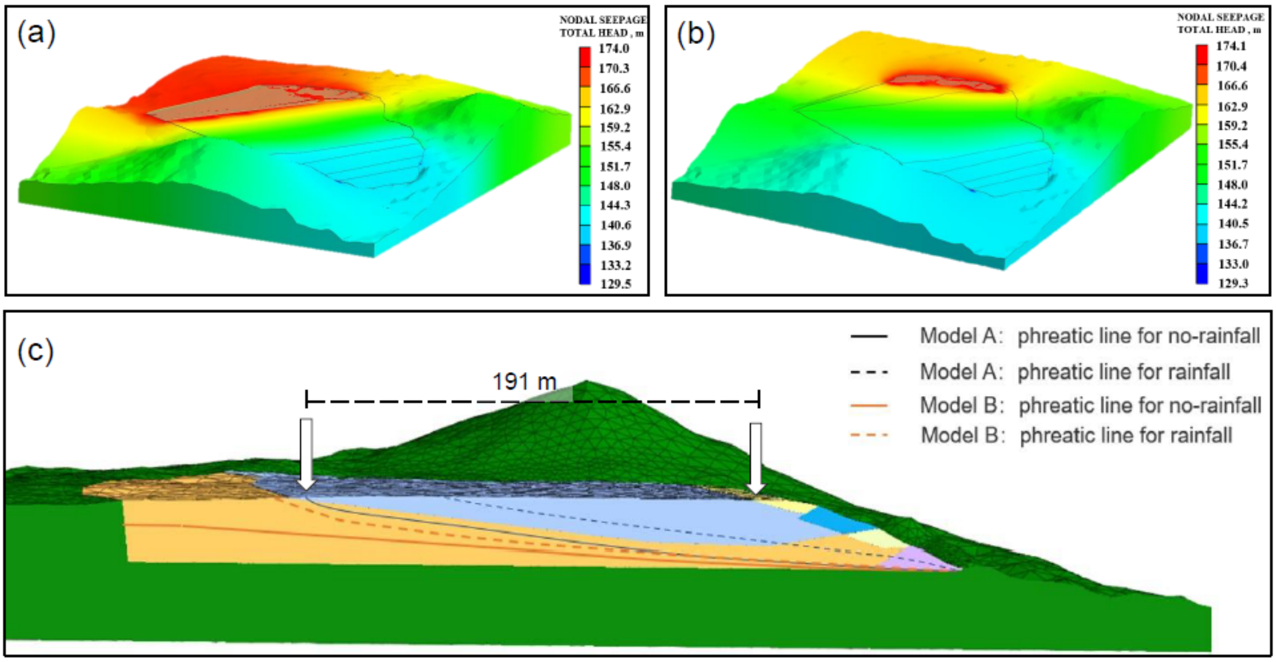


FIG 14 – Comparison of seepage calculation model and phreatic line distribution.

Simulation under rainfall conditions allows for prediction of the phreatic line in the tailings pond, as shown in Figure 14c. Analysis of the calculation results reveals discrepancies in the phreatic line levels between models A and B under non-rainfall conditions. Model A's phreatic line is approximately 191 m from the top of the dam, while Model B's profile indicates that, even after accounting for rainfall, its phreatic line remains below that of Model A under non-precipitation conditions. This highlights the significant impact of water level delineation on seepage simulation results in three-dimensional conditions.

The phreatic line is a critical indicator for assessing the safety of tailings ponds. Tailings particles below the phreatic line are in a saturated state. When the phreatic line rises, the shear strength of the tailings material decreases due to the effect of seepage water, reducing the sliding resistance of the slope and increasing the sliding force, thereby leading to a decline in stability, demonstrating that a 1 m increase in the phreatic line height can result in a stability decrease of 0.05 or more. According to the Chinese 'Safety Regulations for Tailings Ponds' (GB, 39496–2020), for tailings dams with heights below 30 m, the phreatic line depth should be maintained at more than 2 m. The central cross-section of the dam as a typical profile was selected for analysis. In models A and B, under both no-rainfall and rainfall conditions, the maximum depths of the phreatic line were 8.66, 4.55, 8.67 and 8.66 m, respectively, which comply with safety regulations. Model B results indicate higher seepage stability, while model A results are more conservative.

UAV-GENERATED DATA FOR TAILINGS DAM BREACH ANALYSIS (TDBA)

Tailings dam breach analysis (TDBA) is essential for predicting sediment transport during potential tailings dam failures and assessing site planning suitability. Guidelines from the International Council on Mining and Metals (ICMM, 2020) and China's 'Outline for Preparation of Safety Facility Design for Non-Coal Mining Construction Projects' mandate TDBA to evaluate the extent of potential tailings pond failures and plan emergency measures to mitigate disaster impacts. Factors such as peripheral topography, tailings particle gradation, dam failure volume, and rheological modelling significantly influence TDBA outcomes.

Topography and geomorphology surrounding the tailings pond play a crucial role in debris flow patterns and impact zones. UAV technology enhances TDBA by providing precise terrain modelling, thereby increasing reliability.

Comparisons between TDBA scenarios in flat downstream terrain and gully terrain utilise high-precision UAV-generated terrain data and the Smooth Particle Hydrodynamics (SPH) simulation method for dam failure analysis. Figure 15 illustrates SPH-based simulation of tailings pond failure in flat topography downstream, where instantaneous dam failure converts gravitational potential energy into kinetic energy. The resulting tailings mudflow travels downstream from the dam breach site at speeds exceeding 8 m/s. While Figure 16 depicts SPH simulation of tailings pond failure in gully topography downstream. Here, the tailings follow low-gradient gullies before spreading across open topography. Impact with high terrain alters flow dynamics, directing debris towards mountainous terrain and spreading laterally. Terrain type significantly influences post-collapse debris flow patterns, with UAV-derived high-precision terrain data improving prediction accuracy and reliability.

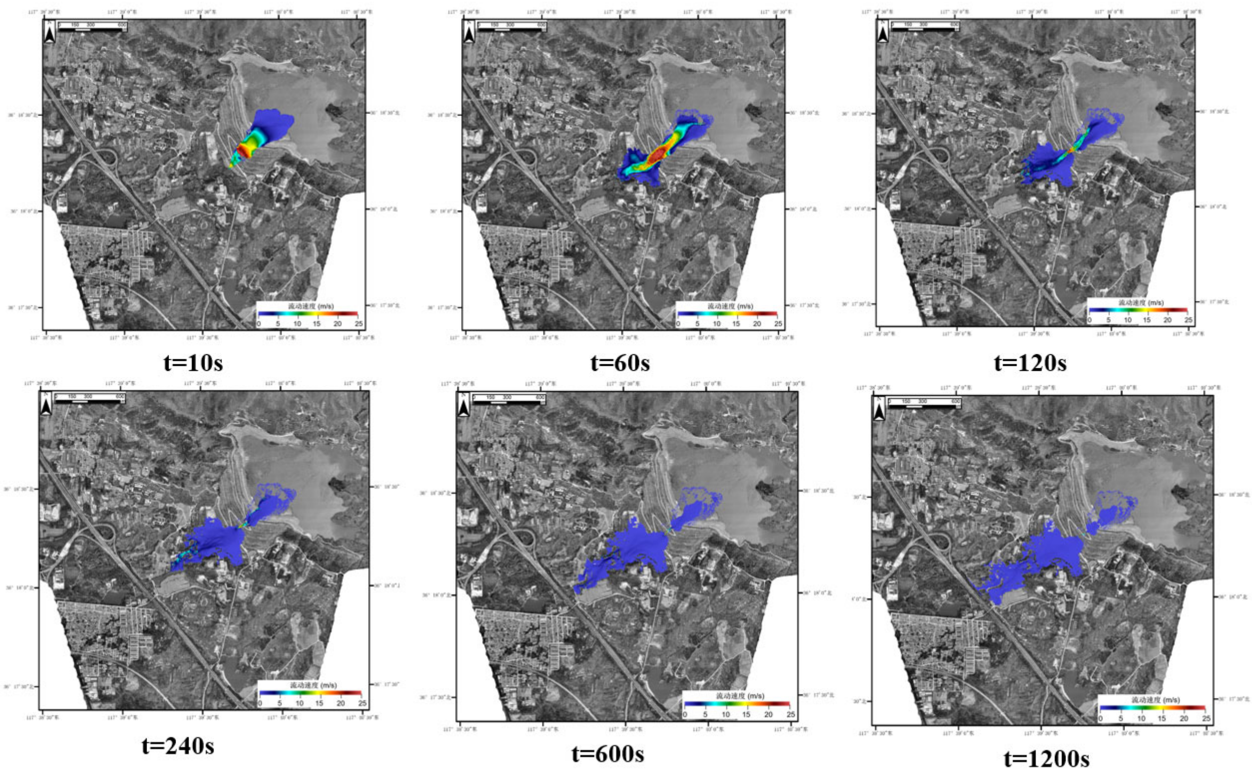


FIG 15 – TDBA results in a downstream flat topography.

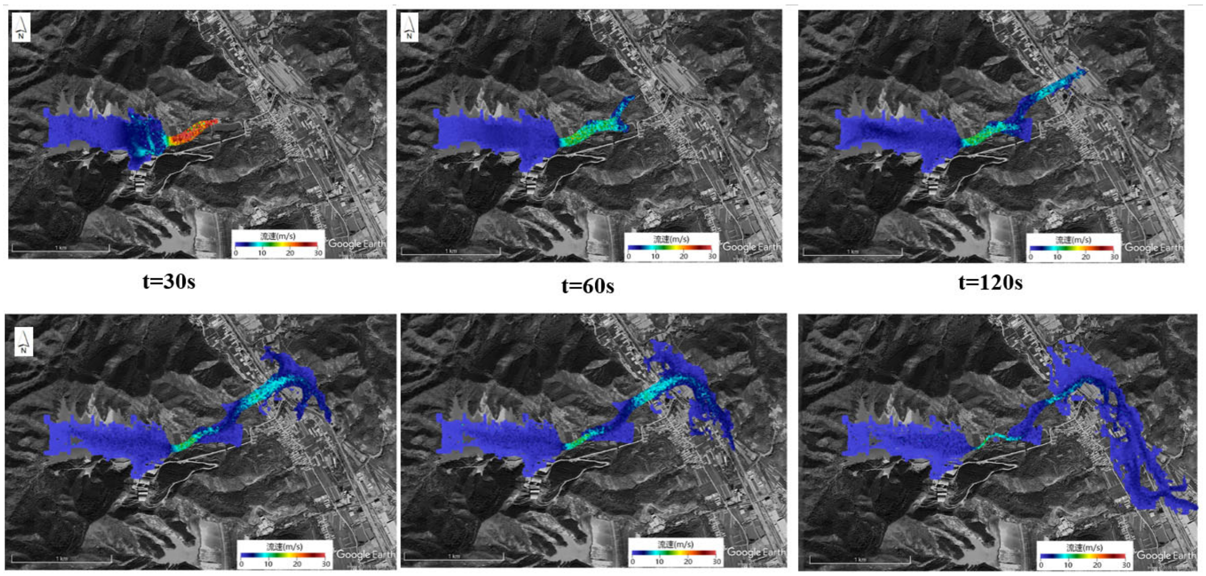


FIG 16 – TDBA results in a downstream gully topography.

FUTURE VISION

UAV monitoring enables comprehensive cross-sectional data monitoring without blind spots, significantly expanding online monitoring capabilities. UAV operations are characterised by simplicity, affordability, practicality, and economic feasibility. Integrated UAV airports facilitate automatic charging, daily remote data collection, and transmission, enhancing efficiency across various sectors including public security, forestry, and electric power. This approach reduces risks for site inspectors and accelerates task completion.

Regular automatic inspections of tailing ponds by UAVs involve gathering visible light, LiDAR, and infrared thermal imaging data to capture operational parameters. This data supports daily monitoring to detect surface cracks in tailing pond dams, foreign objects in drainage systems, geological hazards in surrounding areas, and assess drainage system functionality. Periodic calculations include sedimentary beach indices and safety coefficients of tailing ponds, complemented by monitoring rainfall, tailing discharge rates, and surface displacements.

Integrating daily operational data into a centralised database enables predictive analysis of dam stability using advanced forecasting methods. UAVs also serve critical functions such as intrusion detection, remote broadcasting, and emergency lighting, significantly enhancing safety management and disaster prevention capabilities for tailing ponds.

REFERENCES

Chugh, A K, 2014. Influence of valley geometry on stability of an earth dam, *Canadian Geotechnical Journal*, 51(12):07–17.

Clarkson, L and Williams, D, 2020. Critical review of tailings dam monitoring best practice, *International Journal of Mining, Reclamation and Environment*, 34(2):119–148.

Ho, H, 2014. Parametric studies of slope stability analyses using three-dimensional finite element technique: geometric effect, *Journal of GeoEngineering*, 9(1):33–43.

Hu, J, Hu, S, Kang, F and Zhang, J, 2013. Real-Time Dry Beach Length Monitoring for Tailings Dams Based on Visual Measurement, *Mathematical Problems In Engineering*, 2013(1):1–7.

Hudson-Edwards, K, 2016. Tackling mine wastes, *Science*, 352:288–290.

International Council on Mining and Metals (ICMM), 2020. Global Industry Standard on Tailings Management, August 2020.

Jewell, R J, 2012. Putting beach slope prediction into perspective, *Journal of the Southern African Institute of Mining and Metallurgy*, 112(11):927–32.

Justo, J L, Morales-Esteban, A, Justo, E, Francisco, A J, Percy, D and Vázquez-Boza, M, 2019. The dry closure of the Almagrera tailings dam: detailed modelling, monitoring results and environmental aspects, *Bulletin of Engineering Geology and the Environment*, 78(3):1–15.

Kumar, S, Choudhary, S S and Burman, A, 2023. Recent advances in 3D slope stability analysis: a detailed review, *Modeling Earth Systems and Environment*, 9:1445–1462.

Li, A L, 2015. Tailings subaerial and subaqueous deposition and beach slope modeling, *Journal of Geotechnical and Geoenvironmental Engineering*, 141(1):04014089.

Rana, N M, Delaney, K B, Evans, S G, Deane, E, Small, A, Adria, D A, McDougall, S, Ghahramani, N and Take, W A, 2024. Application of Sentinel-1 InSAR to monitor tailings dams and predict geotechnical instability: practical considerations based on case study insights, *Bulletin of Engineering Geology and the Environment*, 83(5):204.

Ruan, S L, Han, S M, Lu, C W and Gu, Q H, 2023. Proactive control model for safety prediction in tailing dam management: Applying graph depth learning optimization, *Process Safety and Environmental Protection*, 172:329–340.

Wu, H, Nian, T, Chen, G, Zhao, W and Li, D, 2020. Laboratory-scale investigation of the 3-D geometry of landslide dams in a U-shaped valley, *Engineering Geology*, 265:105428.

Wu, H, Nian, T, Shan, Z, Li, D, Guo, X and Jiang, X, 2023. Rapid prediction models for 3D geometry of landslide dam considering the damming process, *Journal of Mountain Science*, 20:928–942.

Xu, B and Wang, Y, 2015. Stability analysis of the Lingshan gold mine tailings dam under conditions of a raised dam height, *Bulletin of Engineering Geology and the Environment*, 74:151–161.

Yang, C, Yang, P, Lyu, W S and Wang, K, 2021. Surface deformation monitoring of tailings dam slope based on UAV photogrammetry, *Journal Safety Science and Technology*, 17:5–11.

Yang, J, Sun, Y, Li, Q and Qian, Z, 2019. Measure dry beach length of tailings pond using deep learning algorithm, In *Proceedings of the 2019 International Conference on Robotics,* pp 503–508 (Association for Computing Machinery: New York).

Unmanned aerial vehicle observation technology of coal mining-induced surface movement and fissures

B Wei[1], K Wang[2], T Zhao[3] and J Zhang[4]

1. College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590, China. Email: wbw15690273377@163.com
2. Lecturer, College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590, China. Email: kwang@sdust.edu.cn
3. Professor, College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590, China. Email: ztbwh2001@163.com
4. Shandong Ruizhi Flight Control Technology Co. Ltd, Qingdao 266590, China. Email: jyzhang@sdust.edu.cn

ABSTRACT

Understanding mining-induced surface movement and fissures is critical for environmental protection and geological prevention. In this study, image recognition algorithms, satellite remote sensing and unmanned aerial vehicle photogrammetry (UAVP) were combined to identify surface movement and fissures caused by mining, and a case study was conducted in a coalmine in western China, and the following conclusions were obtained:

1. The ResNet-50 network was used to perform the initial secondary classification of cropped Digital Orthophoto Maps. A comparative analysis of effectiveness was then conducted between the DeepLabv3+ and U-Net semantic segmentation models. The results indicated a classification accuracy of 93 per cent for the ResNet-50 model, with the U-Net model exhibiting superior identification performance. The orientation and distribution pattern of fissures are affected by the mining direction, surface location and topographic fluctuations.
2. Using SIFT feature extraction method and K-Nearest neighbour algorithm to identify and match the feature points in orthophoto images at different times T1 and T2, the horizontal displacement direction and displacement amount of the ground surface under different slope conditions are obtained. The results show that in the case of land surface fluctuations, the horizontal movement direction is not completely directed to the centre of the subsidence basin, and the amount of surface horizontal movement is related to the height difference of terrain fluctuations.
3. Horizontal displacement correction is added to reduce the observation error of surface subsidence using UAV remote sensing technology, and then the edge of the surface subsidence basin is observed by combining InSAR technology. The results show that the observation accuracy of surface subsidence is greatly improved after the horizontal displacement correction and InSAR are added. Follow-up research can be integrated with long-range unmanned UAV technology, which promotes the unmanned inspection mode, which has the advantages of risk avoidance, blind spots and operational efficiency.

INTRODUCTION

The north-west region of China is rich in coal resources, with simple geological mining conditions, thick coal seams, shallow burial depth, excellent coal quality, and high mining index, making it easy to carry out large-scale longwall and high-strength mining. However, the large mining space caused by high-intensity mining of thick coal seams is bound to cause severe roof movement and obvious mining pressure in the mining area, and the damage to the overlying strata and surface is also more serious, which is prone to ground subsidence, surface fissures, geological disasters and other hazards (Xi *et al,* 2023), as shown in Figure 1.

FIG 1 – Surface damages caused by mining.

Coal mining induced surface subsidence, fissures, landslides and other disasters have led to increasingly serious ecological and environmental problems (Bai *et al,* 2022; Liang *et al,* 2023; Yang *et al,* 2022). The traditional measurement methods for mining surface subsidence often rely on ground measurement techniques such as total station measurement, levelling measurement, GPS, etc. This method has high accuracy and plays an important role in mining subsidence observation. However, in practice, it has exposed the following shortcomings (Li *et al,* 2017; Zhou *et al,* 2019):

- limited coverage
- limited access to information
- the construction cost is high, the monitoring cycle is long, the manual workload is large, and the measuring points are easily damaged.

3D laser scanning and InSAR technology are also applied in monitoring surface subsidence during mining. Although the former has high accuracy, its cost is high and usually cannot be measured in a one-stop manner. The latter also has the problem of spatiotemporal incoherence. These shortcomings limit its promotion and application in mining surface damage monitoring, and there is an urgent need for new methods and technologies to supplement traditional subsidence monitoring methods.

In response to the above issues, this article takes a coalmine in western China as the research object. Based on UAV remote sensing technology (Wang *et al,* 2020; Zhang *et al,* 2023), this article studies the methods of UAV data collection, analyses the three-dimensional movement of the surface and the laws of surface subsidence, and provides a basis for the scientific and efficient management of the ecological environment and disaster prevention in coal mining subsidence areas.

IDENTIFICATION OF SURFACE FISSURES CAUSED BY MINING

Methods

ResNet-50 network for image classification

ResNet-50 (He *et al,* 2016) is a convolutional neural network (CNN) that excels at extracting image features. It consists of 50 convolutional layers, including 49 convolutional layers and one fully connected layer. The structure can be divided into seven parts, as shown in Figure 2. In the first part, the input image undergoes convolution, regularisation, ReLU activation function, and max pooling operation. These calculations generate feature information for the input image, doubling the number of feature channels and halving the size of the input image. The second, third, fourth, and fifth parts are composed of residual blocks, which include convolutional blocks and identity blocks. The Conv block changes the size of the residual block while retaining its size. The identity block deepens the network, allowing it to learn other functions. Starting from the image input with a size of 224 × 224

× 3, the first five parts of the convolution calculation produce an output of 7 × 7 × 2048. The pooling layer in Part 6 converts the output into a feature vector, and finally, the classifier in Part 7 calculates the feature vector and outputs the class probability.

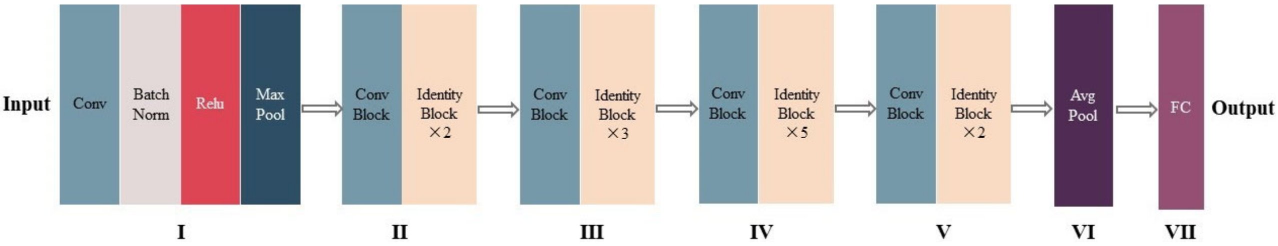


FIG 2 – Structure diagram of ResNet-50 network model.

DeepLabv3+ semantic segmentation models

Introduced by Google researchers in 2018 (Chen *et al,* 2018), DeepLabv3+ is a state-of-the-art CNN model specifically designed for semantic segmentation tasks and represents the latest upgraded version of the DeepLab series models. It has achieved remarkable performance and found wide application in the domain of semantic segmentation (Wang *et al,* 2022). As shown in Figure 3, DeepLabv3+ consists of two main components: an encoder and a decoder. On the network side, the encoder uses the MobileNet model as the backbone network, and combines it with the ASPP (Atrous Spatial Pyramid Pooling) module to carry out effective feature extraction. The feature map of the MobileNet backbone network is divided into two branches: one branch provides the feature map output of the last layer of the backbone network and sends it to the ASPP module, while the other branch provides the shallow feature map of the middle layer of the backbone network and forwards it to the decoder module. In the decoder module, the shallow feature map is integrated with the high-level semantic features generated by the ASPP module. The convolutional convolutions or up-sampling operation ensures that the two input feature plots have the same size. These maps are then concatenated and further processed through a series of 3 × 3 convolution blocks. Finally, an output segmentation map, with the same resolution as the original image is obtained by up-sampling using linear interpolation. The DeepLabv3+ model, equipped with a decoder modules and optimised along the image boundary, excels in producing superior segmentation results. This characteristic makes it particularly well-suited for identification of mining-induced surface-fissures.

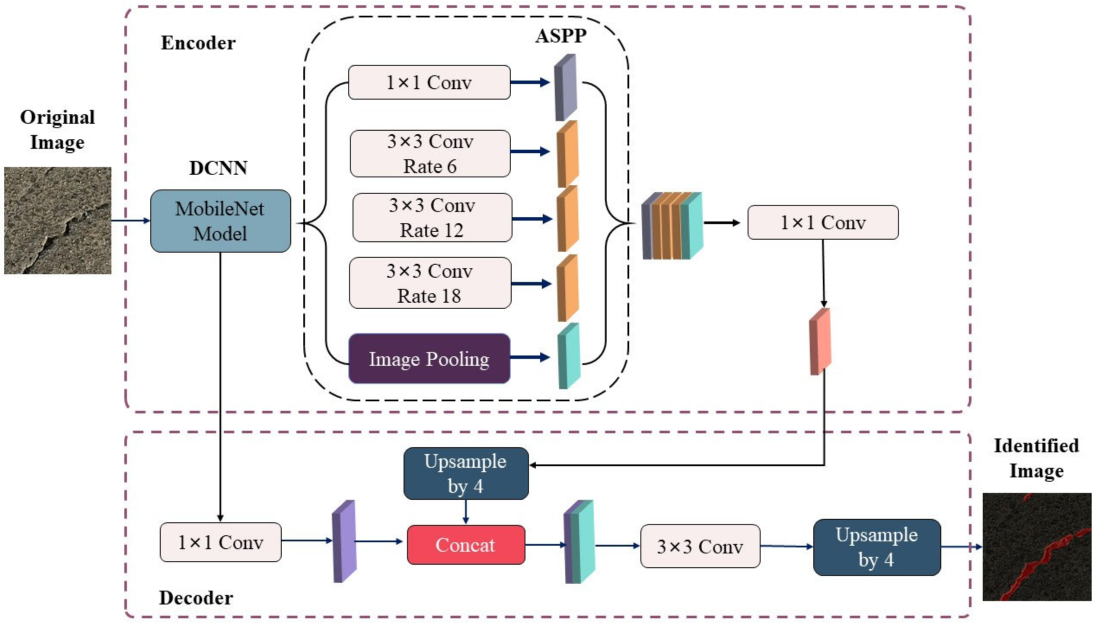


FIG 3 – Structure diagram of DeepLabv3+ semantic segmentation model.

U-Net semantic segmentation models

U-Net (Ronneberger, Fischer and Brox, 2015) is a popular semantic segmentation model based on a full convolutional neural network. The structure employs an encoder-decoder framework to reconstruct the original image. As shown in Figure 4, the left contracting path of the U-shaped network involves stacking, convolving, and pooling the input images to increase the number of output feature channels and capture essential features from the original image. On the right side of the expansive path, deconvolution operations are utilised to gradually restore the image size. Additionally, after each deconvolution operation, the resulting image is combined with the feature map extracted from the left contracting path to restore image features. This allows the entire network to leverage the encoder and generate an image consistent with the original one.

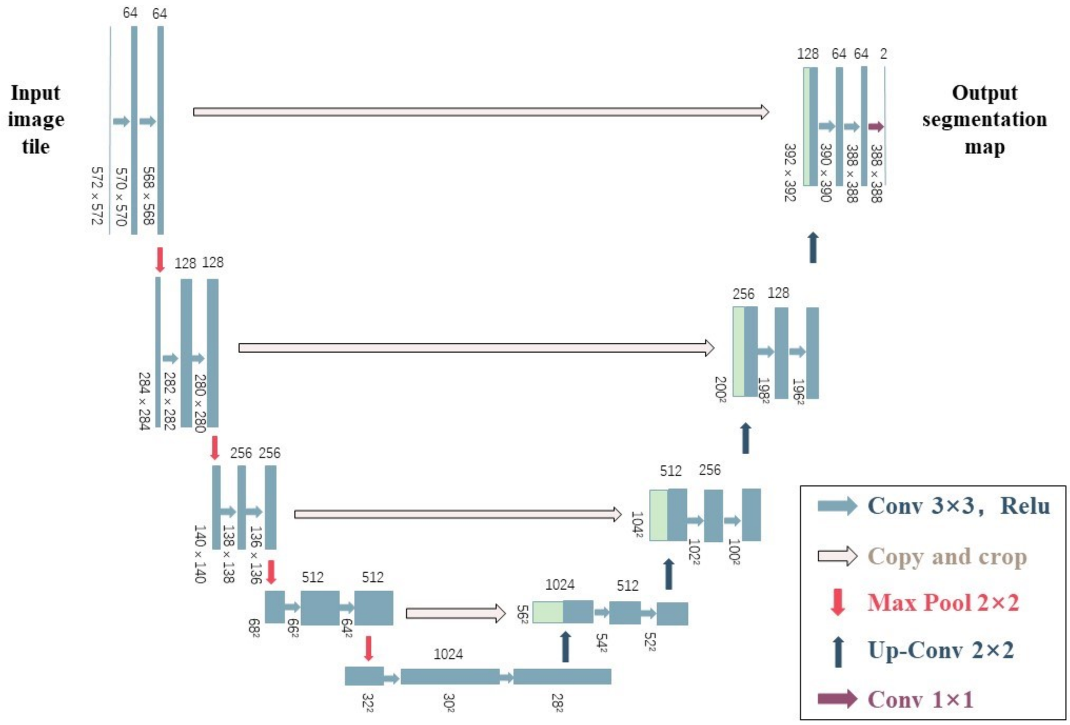


FIG 4 – Structure diagram of U-Net semantic segmentation model.

Research process

Aerial survey of the mining workface surface using a UAV equipped with a visible light camera to obtain workface surface images, The images are then processed to generate Digital Orthophoto Maps (DOMs). A study area is selected and cropped into uniformly sized images. Classification network is utilised to categorise the cropped images into fissure and non-fissure images. A training data set is created to obtain the optimal model parameters. The CNN models are trained on fissures images, then compared to determine the better-performing model in mapping mining-induced fissures. The optimal semantic segmentation model is employed to identify fissures in multi-temporal data. The study area is reconstructed through image stitching, enabling analysis of fissure development patterns in the multi-temporal data, as shown in Figure 5.

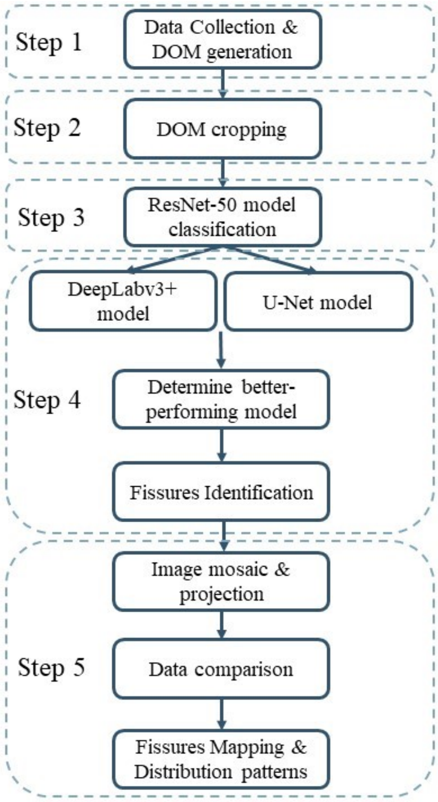


FIG 5 – Structure diagram of U-Net semantic segmentation model.

Research results

Misidentification of models

In this study, the ResNet-50 classification network achieved a respectable accuracy of 93 per cent. However, ResNet-50 classification network exhibits a relatively low number of misclassifications and omissions in fissure images. Analysing the distinctive features of misclassified and missed images can contribute to further enhancing the accuracy of the classification network. Figure 6 illustrates several examples of misclassified images. The classification errors can be attributed to the complex nature of surface attachments and the non-uniform surface illumination resulting from weather conditions. Specifically, misclassification occurs when features such as withered tree branches and collapsed areas possess grey scale values and morphology similar to mining-induced fissures. Additionally, factors such as tree vegetation, mountains, and shadows generated by lighting angles can influence misclassification. To mitigate these issues, several strategies can be implemented. Firstly, flight missions should be scheduled during appropriate time intervals, such as two hrs before or after noon, to ensure favourable lighting and weather conditions. Secondly, the DSM elevation information can be utilised to alleviate the impact of shadows in regions with significant elevation variations, such as gullies. Lastly, manual selection of misclassified images through visual interpretation can be employed.

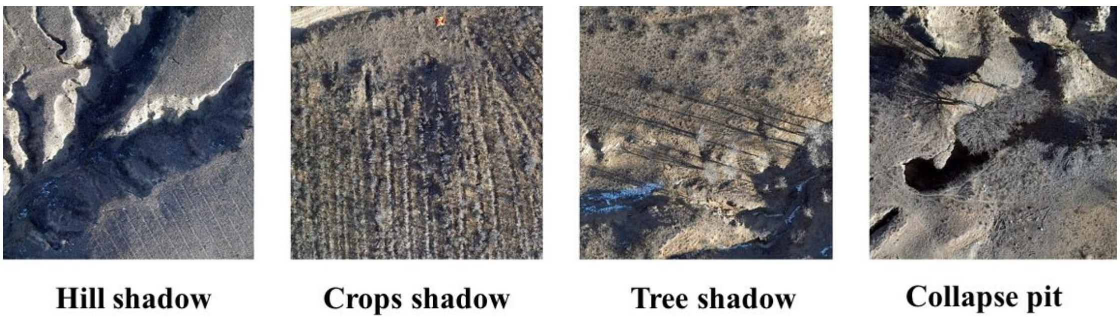


FIG 6 – Examples of misclassified images.

Fissure distribution patterns

The U-Net semantic segmentation model obtained from this study was used to extract fissures in the study area of the third working face, and the results are shown in Figure 7. From Figure 7, it can be seen that a large number of surface fissures are developed within the working face and a small number are developed at the boundary of the working face in the study area. Based on visual interpretation of the identified images, five areas with dense fissures are obtained, as shown in the numbers F1 to F6 in the figure. Among them, the F1 fissure group is located at the boundary of the first working face, and its shape is mainly linear. The fissure distribution is dense, and the spacing is generally about 5 m. The F2 and F3 fissure groups develop near the centreline of the working face, perpendicular to the direction of mining. The length of surface fissures varies greatly, generally ranging from tens to hundreds of metres, and from a few centimetres to tens of centimetres in width. They exhibit the characteristic of having the largest width in the centre of the working face and gradually decreasing towards the boundary. The F4 fissure group is located in front of the cutting eye of the first working face, and the fissure shape is mainly arc-shaped, mostly arranged in parallel with a spacing of about 10 m. The opening direction is basically opposite to the direction of the working face recovery. The fissure groups F5 and F6 are jointly affected by three working faces and are located at the boundary of the third working face. The fissures here are extremely dense, with a spacing of less than 5 m. The extension direction is roughly parallel to the working face groove, and the fissure morphology is mostly arc-shaped, facing the goaf of the third working face.

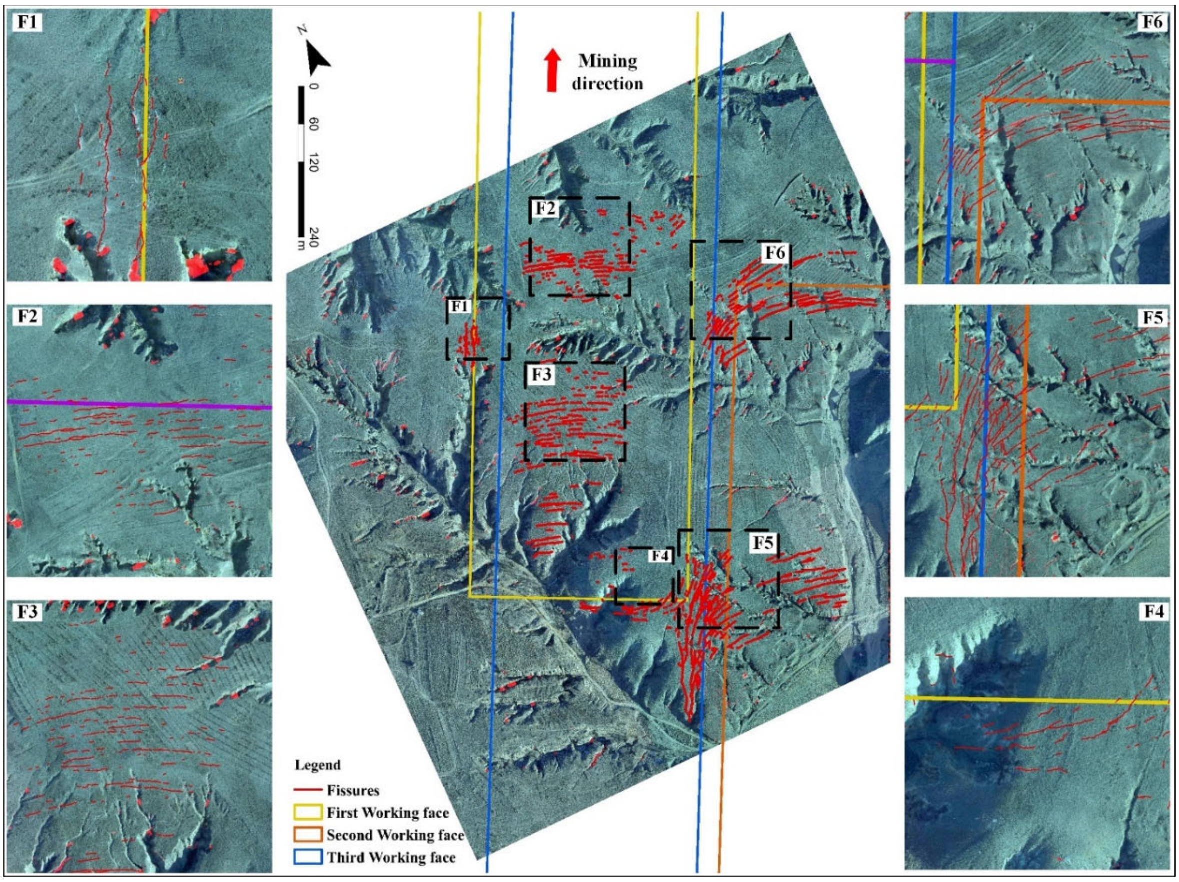


FIG 7 – Fissure segmentation and extraction results.

Fissure distribution patterns on the workface centre and old goaf areas

The F2, F3, and F4 fissure groups are located within the ground projection range of the third workface centre. The orientations of these fissures are generally perpendicular to the direction of workface retreat, exhibiting a slightly arcuate and parallel spaced distribution. The arc centres are all directed towards the downhill side of the slope, ie in the direction of significant elevation decrease, as illustrated in Figure 8. The maximum elevation differences within the F2, F3, and F4 fissure group areas are approximately 18 m, 36 m, and 18 m, respectively. It is noteworthy that in the north-east direction of the F2 and F3 fissure groups and the south direction of the F4 fissure group, the elevation change on the ground is within the range of 3–9 m, and fissures are sparsely distributed in these areas. Consequently, it can be inferred that the occurrence or duration of fissures is closely related to the ground topography. Mining in areas with significant elevation differences and slopes facing towards the centre of the subsidence basin can lead to the formation of extensive spaced fissure groups. The eastern part of the F5 and F6 fissure groups exhibits an arcuate distribution, with the overall arc centre direction facing towards the downslope of the slope, where the elevation significantly decreases according to the DSM. In conclusion, the orientation and distribution pattern of fissures are not only influenced by the mining direction and ground position but are also closely associated with the undulations in ground topography.

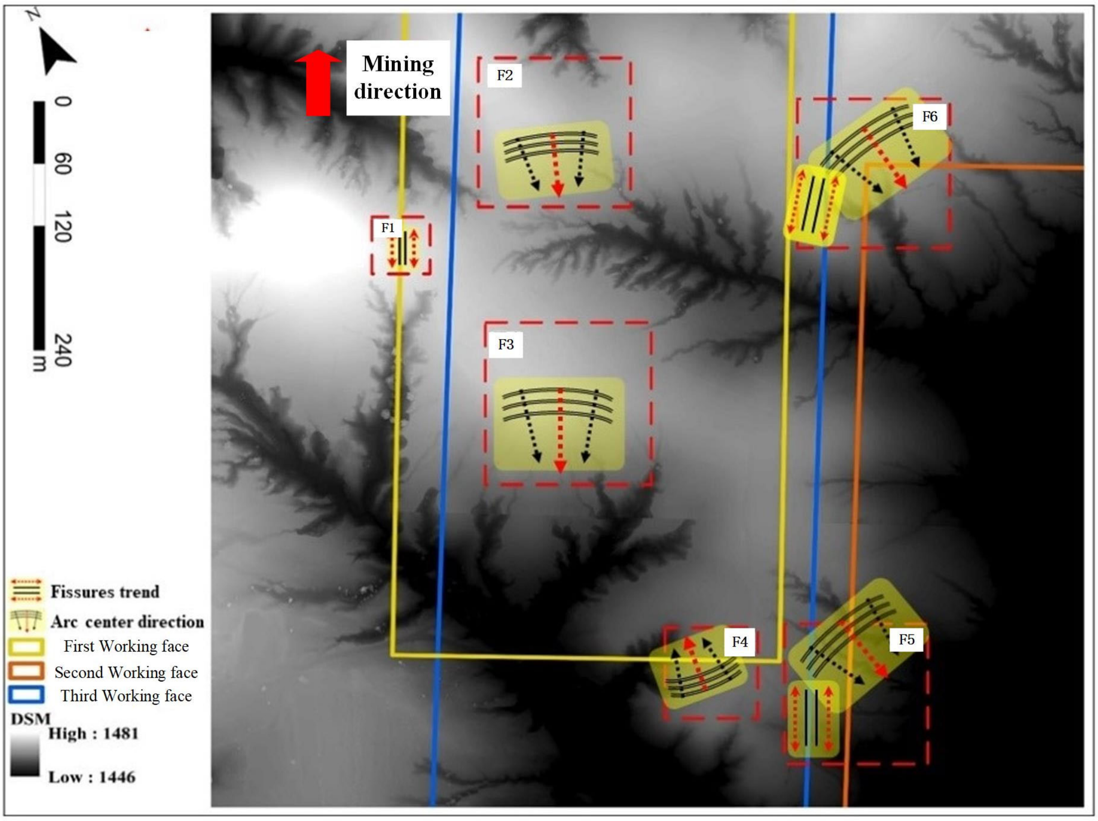


FIG 8 – Fissure trend and arc centre direction on the DSM base map.

IDENTIFICATION OF SURFACE HORIZONTAL DISPLACEMENT

Methods

SIFT feature extraction method

The SIFT feature extraction method, also known as scale invariant feature transformation, is an algorithm that detects local characteristics of an image. Its principle is to find feature points on the spatial scale of the image and calculate their directions and descriptors. This method has good robustness to translation, rotation, scaling, lighting etc when extracting feature points, and can meet the requirements of surface DOM feature recognition in mining areas.

K-Nearest neighbour algorithm

The K-Nearest neighbour algorithm is a widely used similarity indexing method, which involves finding K vectors in the original training data set that are closest to the input vector set for a new input data instance given a training data set. If most of the K feature vectors belong to the same class, then divide the input vectors into this class.

Research process

Using UAV equipped with a visible light cameras to collect data from different time T1 and T2 points in the research area, and processing it to generate DOMs. Identify the feature points in two periods of DOM images and obtain a set of feature points for both images. By matching feature points with the same name in two images, feature point pairs are obtained, As shown in Figure 9.

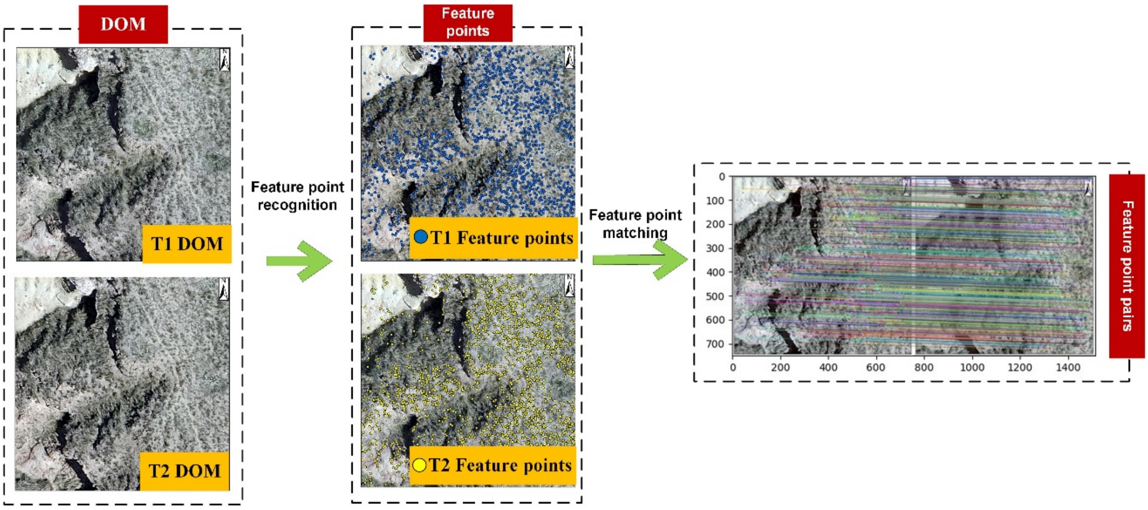


FIG 9 – Horizontal displacement schematic diagram.

Subsequently, the geographic coordinates of each pair of feature points are extracted to obtain a coordinate set, and the displacement size and direction of each pair of features are calculated based on their coordinates, the displacement calculation is shown in Equations 1 and 2, substitute the *i-th* pair of feature points into the equation to calculate the displacement magnitude L_i and direction α_i. Use this method to study the horizontal displacement at different positions on the surface of the earth, and investigate the influence of terrain factors on surface horizontal displacement.

$$\begin{aligned} L_i &= \sqrt{(x_{i2}-x_{i1})^2+(y_{i2}-y_{i1})^2} \\ &= \sqrt{\Delta x_i^2+\Delta y_i^2} \end{aligned} \tag{1}$$

$$\alpha_i = \begin{cases} \arctan\left|\dfrac{\Delta x_i}{\Delta y_i}\right|, (\Delta x_i>0, \Delta y_i>0) \\ 180^\circ - \arctan\left|\dfrac{\Delta x_i}{\Delta y_i}\right|, (\Delta x_i>0, \Delta y_i<0) \\ 180^\circ + \arctan\left|\dfrac{\Delta x_i}{\Delta y_i}\right|, (\Delta x_i<0, \Delta y_i<0) \\ 360^\circ - \arctan\left|\dfrac{\Delta x_i}{\Delta y_i}\right|, (\Delta x_i<0, \Delta y_i>0) \end{cases} \tag{2}$$

Research results

Figure 10 shows the variation curve of surface horizontal movement during the mining period. It can be seen from the graph that the surface horizontal movement is divided into two parts: positive horizontal movement and negative horizontal movement. The height difference of slope A is about 12 m, indicating a positive movement. The height difference of slope B is 8 m, indicating negative movement. The maximum positive movement is 83 cm, and the maximum negative movement is 54 cm. As shown in Figure 10:

- Under the influence of terrain, the horizontal movement does not point to the centre of the subsidence basin, but points to the bottom or top of the slope.
- The horizontal movement is related to the height difference of the slope, and the larger the height difference of the slope, the greater the horizontal movement.

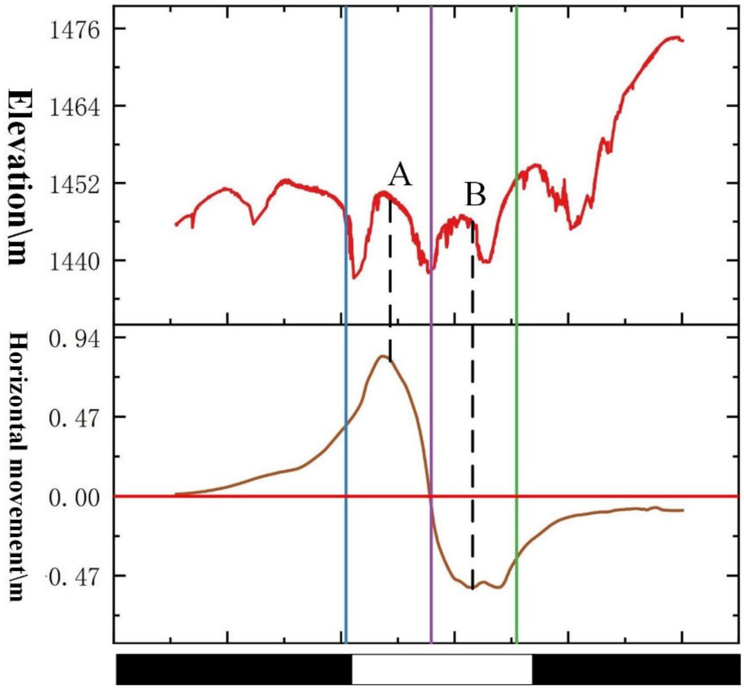


FIG 10 – Elevation, horizontal displacement of slope.

CORRECTION OF SURFACE SUBSIDENCE OBSERVATION DOD METHOD

Methods

DoD Method

UAV remote sensing technology often uses the Difference of DSM (DoD) method to observe surface subsidence, as shown in Figure 11. UAV collect data at different times T1 and T2, and process them separately to generate two periods of DSM. The subsidence basin is obtained by differential processing of the two periods of DSM.

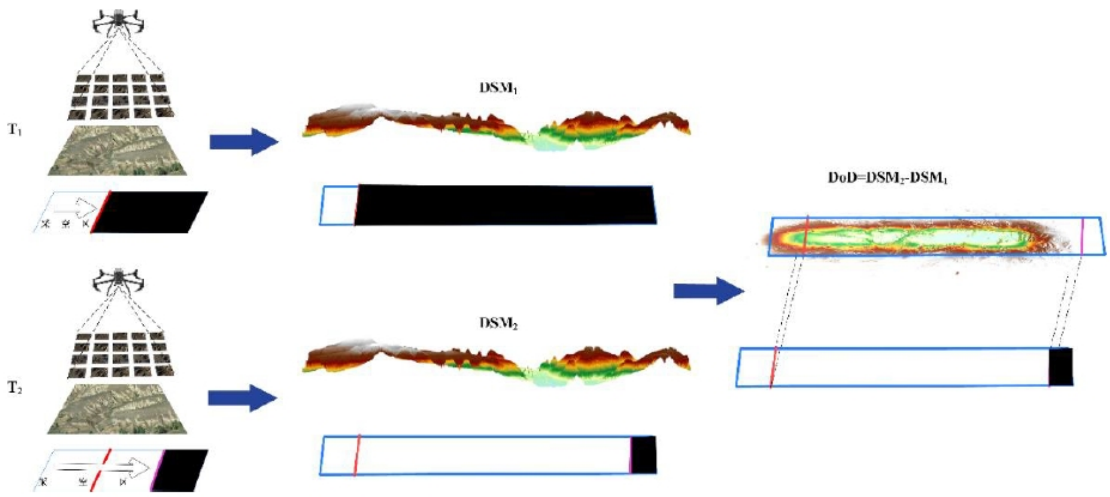


FIG 11 – Principle of surface subsidence model acquired by UAV remote sensing technology.

Shortcomings of the DoD method

Before and after surface subsidence, the subsidence curve obtained by DoD contains noise, especially in areas with significant altitude fluctuations. The main reason for the formation of noise is that under the horizontal movement of the surface, the edge of the valley may become the bottom of the valley, or the bottom of the valley may become the edge of the valley, leading to abnormal subsidence and affecting the observation of DoD subsidence. As shown in Figure 12, The dark yellow dashed line represents the changes in ground subsidence observed manually, while the black dashed line represents the changes in ground subsidence observed by the DoD method.

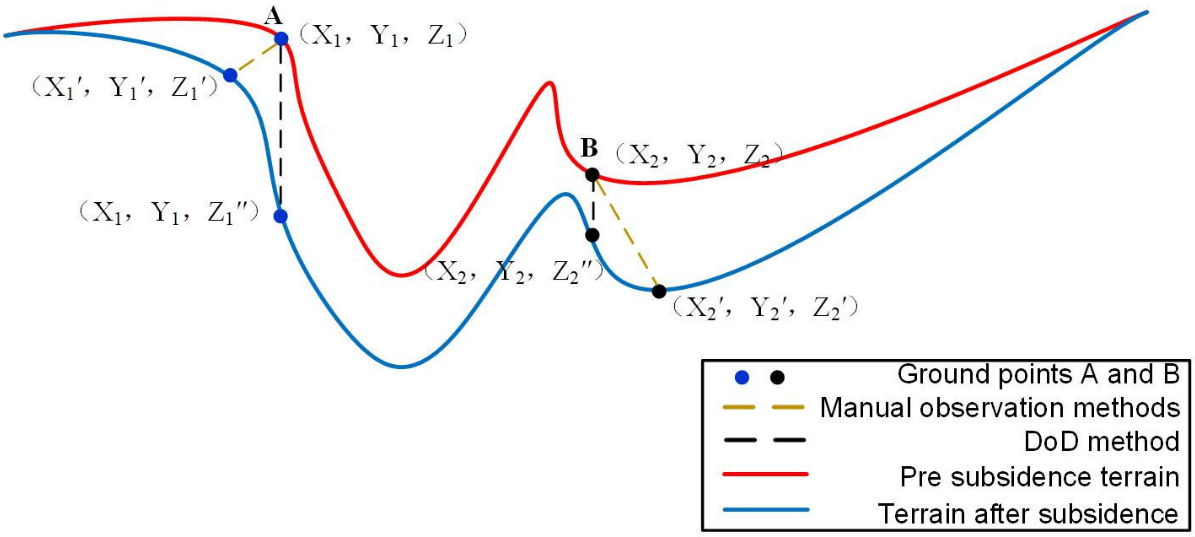


FIG 12 – Schematic diagram of the impact of terrain changes before and after subsidence on DoD measurements.

A method for observing surface subsidence using DoD combined with horizontal movement correction

Based on the above research analysis, if the DoD method is used to obtain the subsidence curve, there will be noise points in the curve due to surface elevation differences and horizontal movement. Therefore, this study analysed the magnitude and direction of surface movement, corrected the geographical coordinates of ground points, and obtained the corrected subsidence curve.

Research results

From Figure 13, it can be seen that there are many undulating noise points on the curve before and after the correction at mining position 1. The maximum subsidence value is at the noise point position, about 5 m, and then the curve changes from rough to smooth; After adding horizontal movement correction, the fluctuation noise of the sinking curve decreases and becomes a smoother curve, with a maximum sinking value of about 4 m. From the graph, it can be seen that in the first half of the sinking curve, there is a significant difference between the curves before and after correction, mainly manifested by the presence of many undulating noise points in the curve before correction, while the curve after correction is relatively smooth. In the second half of the curve, the curves before and after correction are relatively smooth, and the two curves basically overlap. Research has shown that the DoD method with horizontal movement correction can obtain a smoother subsidence model, making subsidence observations more accurate.

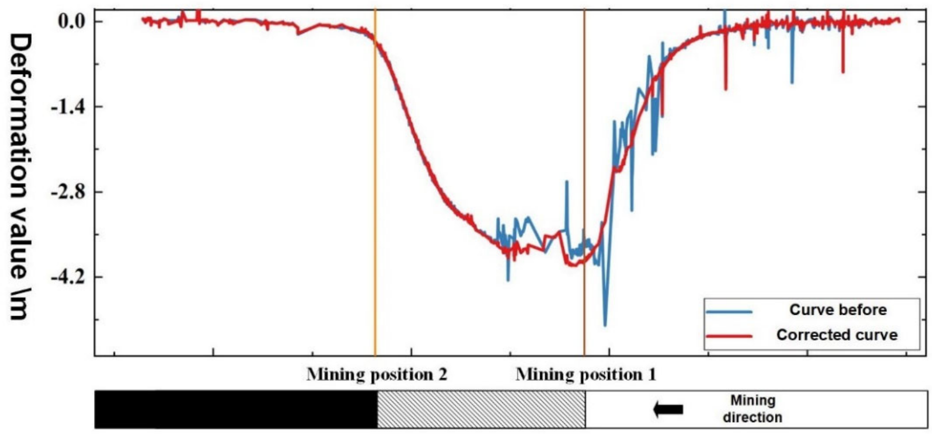


FIG 13 – Schematic diagram of horizontal movement deformation.

PROSPECT

By introducing the unmanned UAV charging and data upload station technology, the advantages of employing UAV for the remote and unmanned mapping of mining-induced fissures become increasingly promising. The schematic diagram of this remote unmanned approach is illustrated in Figure 14. UAV follow pre-established flight paths to conduct inspections of active workface ground. Upon returning, UAV utilise charging and data upload stations installed in nearby stable ground surface to recharge batteries and upload imagery data. The remote data processing centre then receives the transmitted data, and uses this study to quickly annotate the direction of fissures and draw surface subsidence curves. Ultimately, information on the location, length, and width of cracks, as well as surface subsidence, is visualised and pushed to mining operators to facilitate decision-making and implement necessary measures.

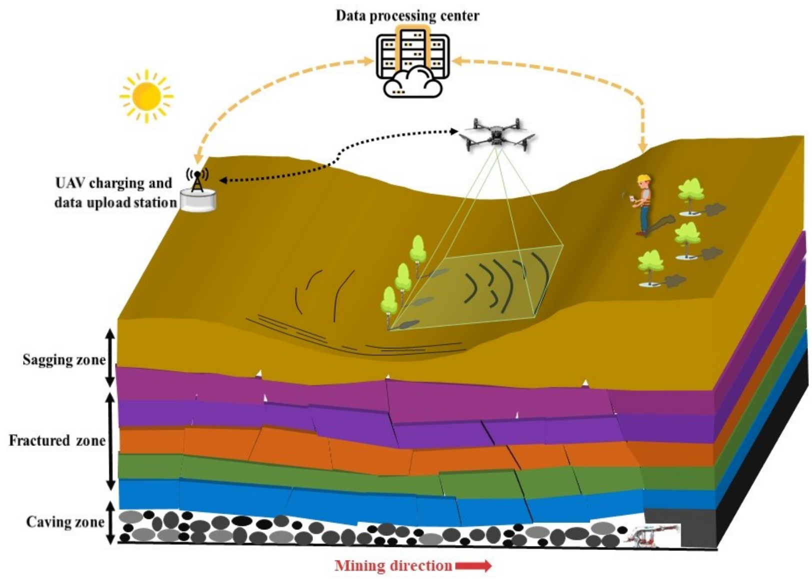


FIG 14 – Future outlook diagram.

CONCLUSIONS

Underground coal mining will inevitably affect surface changes, and observing surface movement during mining is of great significance in terms of both economic and social benefits. This article utilises emerging unmanned aerial vehicle remote sensing technology to reconstruct DOM results by collecting surface unmanned aerial vehicle remote sensing data. Combining semantic segmentation models, SIFT feature recognition algorithms, and K-Nearest neighbour algorithms, it extracts and identifies data on surface subsidence, horizontal movement, and surface fissures, and obtains the law of surface movement. The specific conclusions of this study are as follows:

- The research results indicate that the accuracy of ResNet-50 network in image classification can reach 93 per cent, meeting the requirements of image classification. Among these two semantic segmentation models, U-Net performs better in overall recognition and outperforms DeepLabv3+in segmentation evaluation metrics. MPA reached 90.73 per cent, MIoU reached 83.98 per cent, and F1 score reached 90.67 per cent. The U-Net network model is more suitable for identifying mining-induced fractures under similar conditions in mining areas.
- Using SIFT feature extraction method and K-Nearest neighbour algorithm to extract and recognise feature points with the same name from two cycles of DOM, and then extract horizontal displacement. The horizontal displacement observation method was used to obtain phased horizontal displacement data of the working face, and its impact law was analysed in combination with terrain data.
- By using UAV remote sensing technology to observe ground subsidence in the working face, it was found that there is a certain degree of error in the UAV remote sensing subsidence observation method compared with traditional observation methods. By introducing horizontal displacement to correct the UAV remote sensing subsidence observation method, the noise of the surface subsidence curve is reduced.
- A remote unmanned approach is proposed integrated with UAS automated charging and data uploading station technology. The anticipated benefits include avoiding potential safety risks, overcoming inspection blind spots, and improving operational efficiency compared to manual inspection. This approach enables mining operators to visually understanding of ground damage during mining process, adjust excavation plans. It aims to prevent geological and environmental hazards such as air leakage through penetrating fissures, landslides, and soil erosion. The findings can contribute to realising the mining industry’s current advocacy for intelligent, labor-saving, and unmanned management approaches. It is recommended to implement this approach in mines with comparable conditions.

REFERENCES

Bai, L, Wang, Y, Zhang, K, Yang, Y, Bao, K, Zhao, J and Li, X, 2022. Spatial variability of soil moisture in a mining subsidence area of northwest China, *Int J Coal Sci Technol*, 9:64.

Chen, L C, Zhu, Y, Papandreou, G, Schroff, F and Adam, H, 2018. Encoder-Decoder with Atrous Separable Convolution for Semantic Image Segmentation, in *Proceedings of the European Conference on Computer Vision (ECCV)*, (eds: Ferrari, V, Hebert, M, Sminchisescu, C and Weiss, Y), pp 833–851 (Springer International Publishing: Berlin/Heidelberg, Germany).

He, K, Zhang, X, Ren, S and Sun, J, 2016. Deep residual learning for image recognition, in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pp 770–778.

Li, L, Wu, K, Hu, Z, Xu, Y and Zhou, D, 2017. Analysis of developmental features and causes of the ground cracks induced by oversized working face mining in an aeolian sand area, *Environ Earth Sci*, 76:135.

Liang, Y, Yang, Y, Guo, S, Tian, F and Wang, S, 2023. Combustion mechanism and control approaches of underground coal fires: A review, *Int J Coal Sci Technol*, 10:24.

Ronneberger, O, Fischer, P and Brox, T, 2015. U-Net: Convolutional Networks for Biomedical Image Segmentation, *arXiv*, arXiv:1505.04597.

Wang, K, Yang, P, Lv, W S, Zhu, Y L and Yu, G M, 2020. Current status and development trend of UAV remote sensing applications in the mining industry, *Chinese Journal of Engineering*, 42(09):1085–1095.

Wang, Z, Wang, J, Yang, K, Wang, L, Su, F and Chen, X, 2022. Semantic segmentation of high-resolution remote sensing images based on a class feature attention mechanism fused with Deeplabv3+, *Comput Geosci*, 158:104969.

Xi, N, Mei, G, Liu, Z and Xu, N, 2023. Automatic identification of mining-induced subsidence using deep convolutional networks based on time-series InSAR data: A case study of Huodong mining area in Shanxi Province, China, *Bull Eng Geol Environ*, 82:78.

Yang, D, Qiu, H, Ma, S, Liu, Z, Du, C, Zhu, Y and Cao, M, 2022. Slow surface subsidence and its impact on shallow loess in a coal mining area, *CATENA*, 209:105830.

Zhang, J Y, Wang, K, Zhao, T B, Fang, P, Qi, K, Wei, B W and Li, Z Y, 2023. Status and development of UAV remote sensing technology in mining surface subsidence and fracture measuring, *Coal Science and Technology*, pp 1–11.

Zhou, D, Wu, K, Bai, Z, Hu, Z, Li, L, Xu, Y and Diao, X, 2019. Formation and development mechanism of ground crack caused by coal mining: Effects of overlying key strata, *Bull Eng Geol Environ*, 78:1025–1044.

Advanced visual perception in mining – multimodal fusion and enhancement

C Xu[1] and B Li[2]

1. Postdoctoral Fellow, School of Mineral and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: chengpei.xu@unsw.edu.au
2. Associate Professor, School of Mineral and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: binghao.li@unsw.edu.au

INTRODUCTION

Multi-sensor fusion visual perception technology significantly enhances visual perception capabilities in complex and harsh environments by combining visual data from different sensors. This technology is especially useful for scenarios where traditional single visible light sensors, such as standard cameras, struggle due to poor lighting, adverse visual conditions, or other visual obstructions. In environments with low light, smoke, or dust, the performance of conventional visible light sensors degrades, limiting their application. By integrating data from various sensors like radar, infrared thermal imaging, and others, multi-sensor fusion technology provides a more comprehensive and complementary visual solution. This fusion not only enhances the robustness of visual systems but also greatly expands their potential applications in fields like visual surveillance. In recent years, deep learning methods have become the mainstream technology for addressing multi-sensor fusion issues, demonstrating significant advantages in adaptive feature selection compared to traditional machine learning methods. However, deep learning-based multi-sensor fusion algorithms still face several challenges.

The design of network structures is often redundant, lacking effective screening of useful components within multimodal information. Mainstream fusion algorithms focus excessively on improving display effects without adequately considering the needs of downstream applications and tasks. Existing fusion perception algorithms are generally designed for open visual scenes and lack targeted design for complex visual degradation factors present in tunnel environments of mines. Current deep learning methods for designing multi-sensor fusion networks heavily rely on manual experience to create fusion modules. This reliance increases the complexity of network design and can lead to redundancy. Redundant network modules are difficult to identify in end-to-end learning tasks at this stage, significantly slowing down network inference and potentially interfering with the output of fusion perception. Additionally, training these fusion modules typically requires large amounts of well-annotated multimodal data, further increasing implementation difficulty and cost.

For instance, the fusion network design proposed by Li and Wu (2018) focuses on extracting multimodal fusion features, while Zhao *et al* (2020) introduced a feature decomposition mechanism in the feature fusion and extraction modules. Researchers like Zhang and Ma (2021), Xu *et al* (2020), and Liu *et al* (2017) have attempted to improve network structures through dense cascades and the introduction of residual connections. Although these methods have improved the handling of multimodal information to some extent, they still face limitations in distinguishing between useful and redundant information, with redundancy persisting in network designs. Ideally, the design of fusion networks should be more intelligent, guiding network structure design heuristically based on the importance of different modal information for the current task. This would reduce information redundancy and network weights, requiring the development of new algorithms or frameworks capable of automatically identifying and optimising fusion strategies, thereby reducing dependence on manual experience while improving fusion efficiency and network performance.

Current deep learning designs for multi-sensor fusion algorithms often overlook the specific needs of downstream applications and tasks, focusing mainly on enhancing the visual quality of fused data, such as contrast, dynamic range, and pixel edge texture, to meet human visual needs. However, this human-centric enhancement does not necessarily align with the requirements of machine vision systems. For example, in some scenarios, although the fused data may appear clearer and more user-friendly to the human eye, these visual improvements might not aid machines in performing downstream tasks like object detection and segmentation. Studies by Liu *et al* (2022) and others have adjusted the proportion of various modalities in the fusion output using multi-level features extracted by pre-trained networks, while Xu, Wang and Ma (2021) constructed pre-trained networks specifically for fusion tasks based on disentangled representations. These methods attempt to optimise the fusion process through modality weight calculations but often overly rely on these calculations, neglecting the actual needs and impacts of different modal information on downstream tasks. Future research should focus more on aligning fusion algorithms with the specific requirements of downstream tasks. This could involve task-driven learning methods or task-adaptive network designs to optimise fusion strategies. Algorithms should not only be optimised for visual quality but also ensure that the fusion output enhances machine vision system performance, such as improving object detection, scene understanding, and decision-making capabilities. Moreover, developing smarter fusion mechanisms that can automatically adjust and optimise the contribution of different modalities is crucial for enhancing the effectiveness of multi-sensor fusion.

Current mainstream multi-sensor fusion perception algorithms are primarily designed and optimised for open visual environments like roads, parks, campuses, and industrial parks. However, in specific application domains like tunnel environments in mines, these algorithms perform poorly due to a lack of specialised design. The complex visual degradation factors commonly found in such enclosed spaces, including extreme lighting conditions, high dust concentration, high humidity, and highly reflective surfaces, can severely impact the performance and data quality of visual sensors. Since existing fusion perception algorithms are mostly developed based on training data from open environments, there is a significant shortage of training and testing data for tunnel environments in mines, limiting the algorithms' effectiveness and reliability in these special environments.

METHOD

High-precision multi-modal feature aggregation and redundancy removal algorithm

To address the challenges in aligning, matching, and fusing features from visible light imaging with laser and millimetre-wave devices, we propose a high-precision robust multi-source image registration algorithm based on constrained learning. This algorithm constructs an invariant representation space for multi-source features by maintaining the geometric structure and feature similarity of multi-modal data. By incorporating multiple feature alignment constraints, we can extract features from the latent spaces of multi-modal sensor, creating a common multi-source feature representation space that captures significant three-dimensional structures and texture details. This approach reduces the differences between multi-source modalities and enhances the reliability of feature matching and alignment. Further, we propose an iterative feature contrastive learning model that alternately learns transformations between different source features, achieving fine feature fusion while reducing redundancy. This ensures continuous system operation and stability, especially in challenging coal mining environments, and improves decision accuracy by integrating insights from different modalities.

Adaptive heuristic fusion network structure auto-search framework

Manual design of deep fusion network structures often leads to redundancy and heavily relies on designer experience, potentially limiting innovation and efficiency. To reduce human bias and enhance objectivity, we propose an adaptive structural search framework for high-robustness multi-source fusion networks. This framework starts by generating and augmenting multi-modal data tailored to coalmine tunnel environments, addressing data scarcity and ensuring sufficient training data. We analyse the robustness of fusion network structure operations and conduct explicit analyses of multi-source data feature extraction, alignment, and fusion modules to build a robust and efficient search space. Combining this with a data augmentation scheme, we propose an adaptive neural network search for coalmine multi-modal data, eliminating the feature redundancy brought by manual design. This automated approach constructs a robust fusion network structure, significantly improving design efficiency and adapting to specific coalmine tasks, maintaining model performance and accuracy.

Joint optimisation learning of visual fusion effects and downstream tasks

To address the issue of multi-source data fusion focusing solely on overall visual effects and lacking parallel optimisation for downstream tasks, we propose a joint training learning framework that optimises both visual effects and downstream tasks. This framework integrates high-precision multi-modal feature aggregation and multi-source fusion networks to extract semantic common features from visual sources such as visible light, laser, and millimetre-wave data, maintaining the semantic and topological consistency of visual objects under multi-modal fusion. By combining the feature learning process with downstream tasks like segmentation, classification, and detection, we design a unified learning and optimisation framework that enhances both visual effects and downstream task performance. A dual-layer contrastive learning optimisation framework drives the optimisation, focusing on fundamental visual tasks in coal mining environments. This ensures that the fusion network's optimisation aligns with downstream task requirements, improving overall system performance.

Real-time safety warning based on multi-source multi-modal data

Building on the joint optimisation of fused data and basic downstream tasks, we design several sub-tasks related to coal mining safety, shown in Figure 1, including water-coal monitoring, coal flow monitoring, and large foreign object blockage detection. We introduce fusion algorithms at the entrances and exits of coal bunkers to obtain fused visual data. These monitoring tasks are treated as fundamental semantic segmentation and object detection tasks. By jointly optimising upstream and downstream tasks, we design a multi-modal data-based decision-maker for effective early warning of bunker failures. This system combines visual, radar, and lidar data to monitor the coal bunker environment. The decision-maker uses multi-modal data to detect potential safety issues and provide early warnings, ensuring timely response and enhancing overall operational safety.

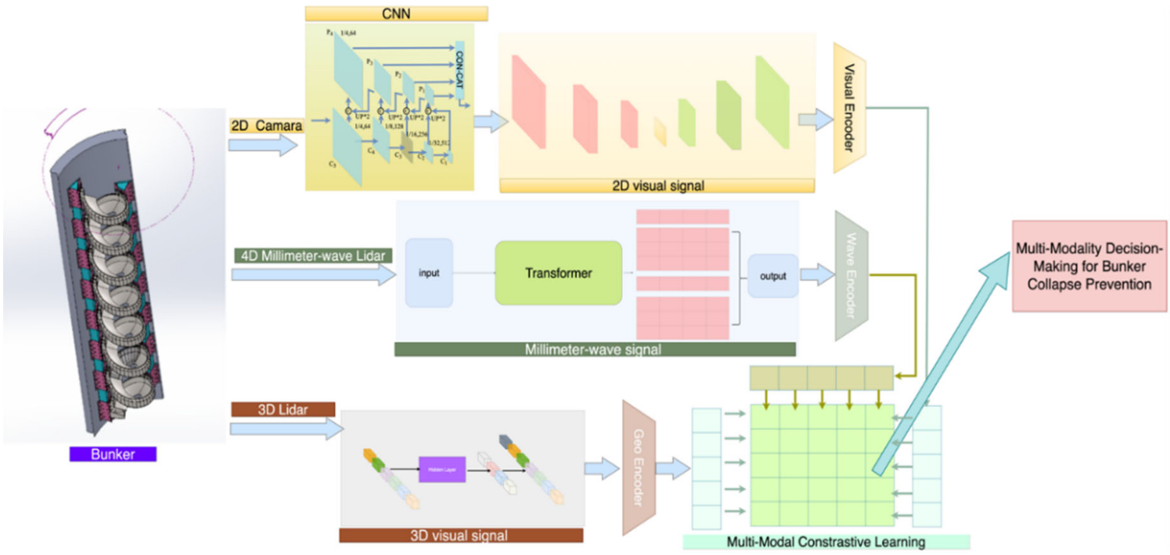


FIG 1 – Real-time safety warning based on multi-modal data.

REFERENCES

Li, H and Wu, X, 2018. DenseFuse: A fusion approach to infrared and visible images, *IEEE Transactions on Image Processing*, 28(5):2614–2623.

Liu, J, Fan, X, Huang, Z, Wu, G, Liu, R, Zhong, W and Luo, Z, 2022. Target-aware Dual Adversarial Learning and a Multi-scenario Multi-Modality Benchmark to Fuse Infrared and Visible for Object Detection, in *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, pp 5792–5801.

Liu, Y, Chen, X, Peng, H and Wang, Z, 2017. Multi-focus image fusion with a deep convolutional neural network, *Information Fusion*, 36:191–207.

Xu, H, Ma, J, Jiang, J, Guo, X and Ling, H, 2020. U2Fusion: A unified unsupervised image fusion network, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 44(1):502–518.

Xu, H, Wang, X and Ma, J, 2021. DRF: Disentangled representation for visible and infrared image fusion, *IEEE Transactions on Instrumentation and Measurement*, 70:1–13.

Zhang, H and Ma, J, 2021. SDNet: A versatile squeeze-and-decomposition network for real-time image fusion, *International Journal of Computer Vision*, 129(10):2761–2785.

Zhao, Z, Xu, S, Zhang, C, Liu, J, Li, P and Zhang, J, 2020. DIDFuse: Deep image decomposition for infrared and visible image fusion, in *Proceedings of the 29th International Conference on International Joint Conferences on Artificial Intelligence*, pp 970–976. https://doi.org/10.24963/ijcai.2020/135

Innovative approaches to dust pollution management in mining operations – a comprehensive image-based identification and evaluation system

J J Yin[1] *and S F Wang*[2]

1. School of Resources and Safety Engineering, Central South University, Changsha 410083, Hunan, Peoples Republic of China.
2. School of Resources and Safety Engineering, Central South University, Changsha 410083, Hunan, Peoples Republic of China. Email: sf.wang@csu.edu.cn

ABSTRACT

Dust pollution poses a persistent challenge within mining processes, giving rise to a spectrum of concerns, including occupational diseases, mechanical degradation, diminished visibility, and the potential for dust explosion incidents. Existing dust detection and monitoring methodologies face limitations, including insufficient measurement accuracy and intricate processing procedures. Consequently, a comprehensive identification and evaluation system rooted in image processing technology is proposed to facilitate real-time measurements of dust pollution in mining worksites.

The study primarily employs grey scale average and fractal dimensions to characterise particle features evident in collected dust images. As a result, the data processing platform can dynamically process data and present dust pollution conditions. Notably, this research integrates the monitoring and assessment of dust pollution with the systematic adjustment of mining parameters, ventilation parameters, and strategies for dust reduction. Through statistical analysis of dust concentration and particle size during mining processes, rock properties such as components and cuttability can inform mining parameters. This information, in turn, guides detailed excavation strategies, including cutterhead speeds, torque, and excavation speed.

Similarly, analysing dust characteristics derived from images is a valuable resource for gaining deeper insights into the efficacy of implemented ventilation strategies. By harnessing vision-based information detailing dust concentration and distribution, a wealth of direct guidance becomes available for refining ventilation parameters. This encompasses crucial aspects such as the selection of appropriate ventilation systems tailored to the specific mining environment and the optimisation of operational conditions for ventilation fans. Additionally, the detailed information derived from the visual data allows for strategic decisions on factors like the spatial arrangement of ventilation outlets and the calibration of airflow rates.

Moreover, precise choices for dust reduction measures and parameters can be made based on the prevailing dust conditions. Upon real-time monitoring of dust pollution using the proposed method, corresponding measures such as spraying and foaming can be promptly implemented. Crucial parameters, such as spray angles and volume, are integral to these application processes. In essence, the proposed method assumes a pivotal role in not only dust monitoring but also the formulation of preventative and control measures within mining processes.

INTRODUCTION

Mining operations are deemed vital for global economic growth and resource supply, providing essential materials for various industries (Trechera *et al*, 2022). However, one of the significant challenges associated with mining activities is the generation of dust pollution (Ji, Yao and Long, 2018; Wang *et al*, 2022b). Dust particles emitted during mining processes are acknowledged to pose health risks to workers and have adverse effects on the surrounding environment and nearby communities. Inhalation of these particles can lead to respiratory problems and other health issues, while the deposition of dust on vegetation and water bodies can disrupt ecosystems and contaminate water sources (Alvarado *et al*, 2015; Fan and Liu, 2021).

Conventional methods for monitoring and controlling dust pollution in mining environments have often been found to fall short in terms of accuracy, efficiency, and coverage (Abbasi *et al*, 2021; Zaid *et al*, 2024). Traditional approaches, such as manual sampling and gravimetric analysis, are widely recognised as being labour-intensive, time-consuming, and providing limited spatial coverage. Furthermore, they may not capture the dynamic nature of dust dispersion, leading to inaccuracies in pollution assessment and management.

In recent years, growing interest has been observed in leveraging advanced technologies to address the challenges of dust pollution in mining operations. Digital image processing and deep learning techniques are seen as promising solutions by enabling real-time, non-invasive monitoring and analysis of dust dispersion (Grasa and Abanades, 2001; Fu and Wang, 2013; Albatayneh, Forsl¨of and Ksaibati, 2019; Li *et al*, 2019). These techniques utilise high-resolution images captured by cameras to extract meaningful features and patterns, allowing for more accurate characterisation and classification of dust pollution levels.

The integration of image processing and deep learning into dust pollution monitoring systems is considered advantageous for several reasons (Wang *et al*, 2022a; Yin *et al*, 2023). Firstly, it allows for the automatic and continuous monitoring of dust dispersion in real time, providing timely insights into pollution levels and trends. Secondly, it enables the extraction of various image features, such as grey scale averages and fractal dimensions, which can be correlated with dust mass and dispersion characteristics. Thirdly, deep learning models can be trained to classify dust pollution levels based on these features, providing a more comprehensive and accurate assessment compared to traditional methods.

This paper proposes a comprehensive method for analysing dust pollution in mining environments using image processing and deep learning techniques. The approach involves conducting physical experiments to simulate dust dispersion, capturing high-resolution images of dust samples, extracting relevant features, and employing deep learning models for classification. The experimental results demonstrate the effectiveness of the proposed method in accurately characterising and classifying dust pollution levels, offering significant potential for enhancing safety and sustainability in mining operations.

EXPERIMENTAL SYSTEM

Dust diffusion simulation experiment

The physical experiment system employed in this study was meticulously designed to simulate the intricate process of dust diffusion within mining environments. Comprising three primary modules, namely the dust generation module, the air-flow control module, and the image acquisition module, this set-up provided a comprehensive platform for conducting controlled experiments. Figure 1 illustrates the experimental system for dust diffusion.

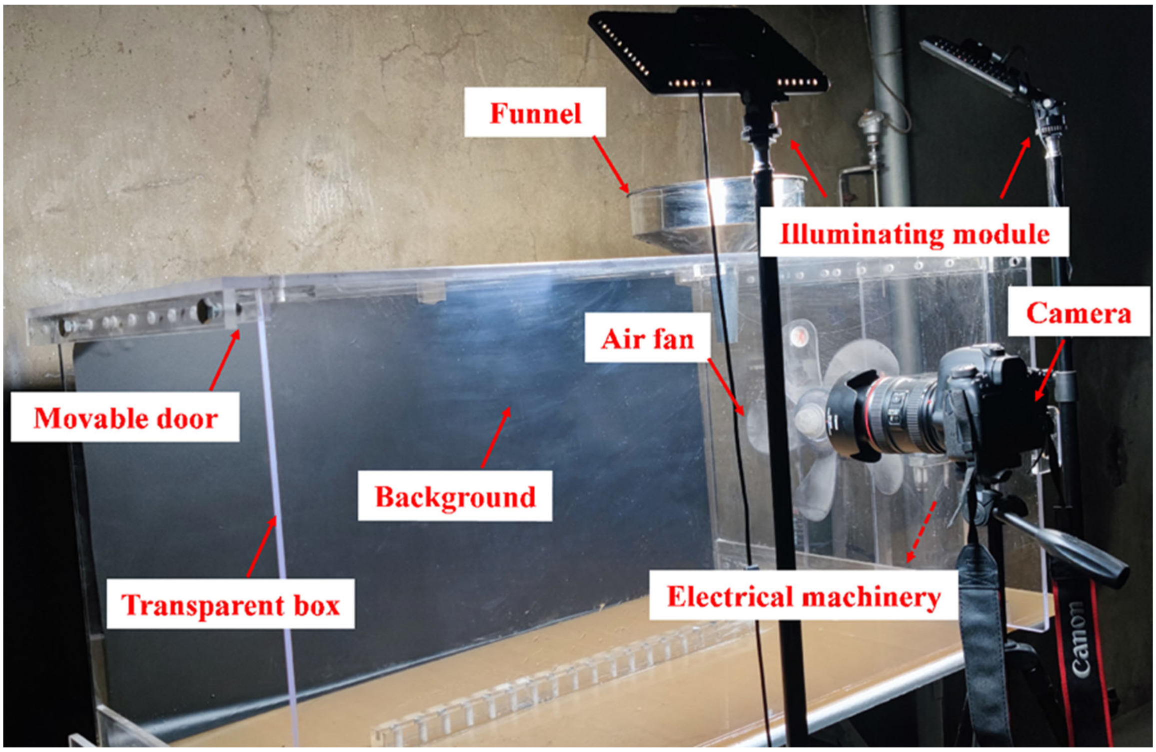


FIG 1 – The physical experimental system for image acquisition of dust samples.

The dust generation module served as the initial stage in the experimentation process, responsible for producing the dust samples utilised throughout the study. Employing precise methodologies, this module ensured the generation of consistent and reproducible dust samples essential for accurate analysis.

In tandem, the air-flow control module played a pivotal role in regulating the airflow within the experimental environment. By maintaining stable airflow patterns and controlling wind velocity, this module facilitated the creation of controlled conditions necessary for studying dust dispersion dynamics.

Finally, the image acquisition module constituted the final component of the experimental set-up, tasked with capturing high-resolution images of the dispersed dust samples. Equipped with advanced imaging technology, this module enabled the acquisition of detailed visual data crucial for subsequent analysis and interpretation.

Experimental procedures

The experimental procedures encompassed a series of meticulously orchestrated steps designed to ensure the systematic execution of the study objectives. These procedures involved meticulous attention to detail and adherence to established protocols to guarantee the reliability and accuracy of the experimental outcomes.

The first step in the experimental protocol involved preparing dust samples. This entailed meticulous drying of the samples to reduce moisture content, followed by precise weighing to ensure consistency across experimental conditions.

Subsequently, a carefully calibrated fan-initiated airflow facilitated the controlled dispersion of the prepared dust samples within the experimental environment. Concurrently, camera parameters were meticulously configured to optimise image capture settings for subsequent analysis.

With the experimental set-up primed and operational, images of the dispersed dust samples were systematically captured using a high-resolution camera. This critical step allowed for the comprehensive documentation of dust dispersion dynamics, providing valuable visual data for subsequent analysis and interpretation.

In summary, the experimental procedures encompassed a meticulously orchestrated series of steps, ranging from preparing dust samples to systematically capturing high-resolution images. Through meticulous attention to detail and adherence to established protocols, the experimental set-up facilitated the systematic investigation of dust diffusion dynamics within mining environments. The equipment components are shown in Table 1.

TABLE 1

Components of the dust diffusion system.

Experimental device	Composition/materials	Parameters
Dust diffusion box	Plexiglass	1.0 m × 0.5 m × 0.5 m
Dust generation module	Funnel	D_u: 23 cm, D_l: 2.5 cm
Air-flow control module	Electric motor	220 V, 50 Hz
	Air fan	Five blades
Image acquisition module	Camera	Canon EOS 6D Mark Ⅱ
	Illuminating apparatus	RUIMA RJ-10 LED 720 LUX,12W
	ASUS Laptop	GeForce 2060, 32 GB
Dust preparation device	Dolomite powder	74 μm/(10 mg–300 mg)
	Dust dryer	JingHong DHG-9036A
	Electronic balance	FA 1004N

RESULTS AND DISCUSSION

Analysis of dust images

Upon the completion of the experimental phase, a comprehensive analysis of the acquired dust images was conducted, yielding valuable insights into the characteristics and behaviour of dust particles within the experimental environment. A total of 300 dust images were meticulously processed, enabling the extraction of key parameters essential for subsequent analysis. Figure 2 presents the image processing processes for the 100 mg dust sample.

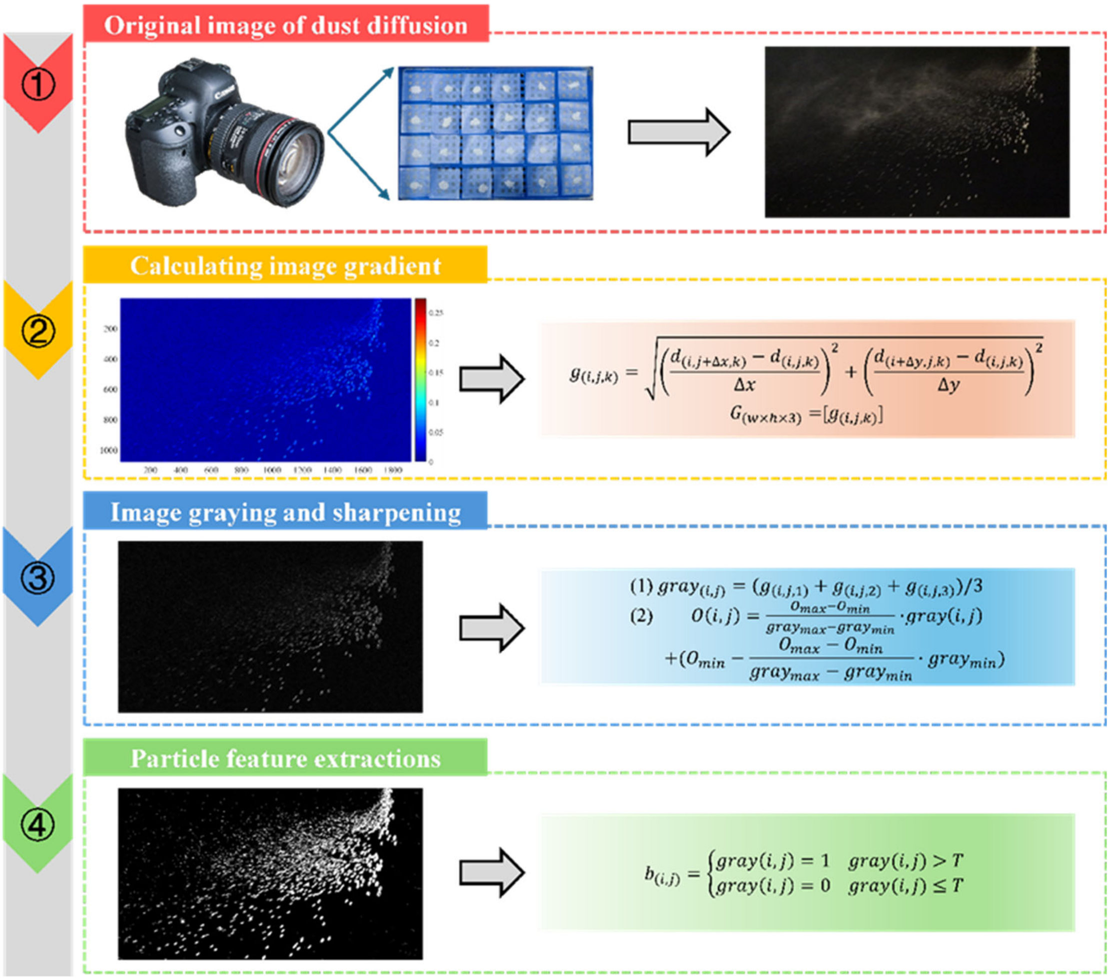
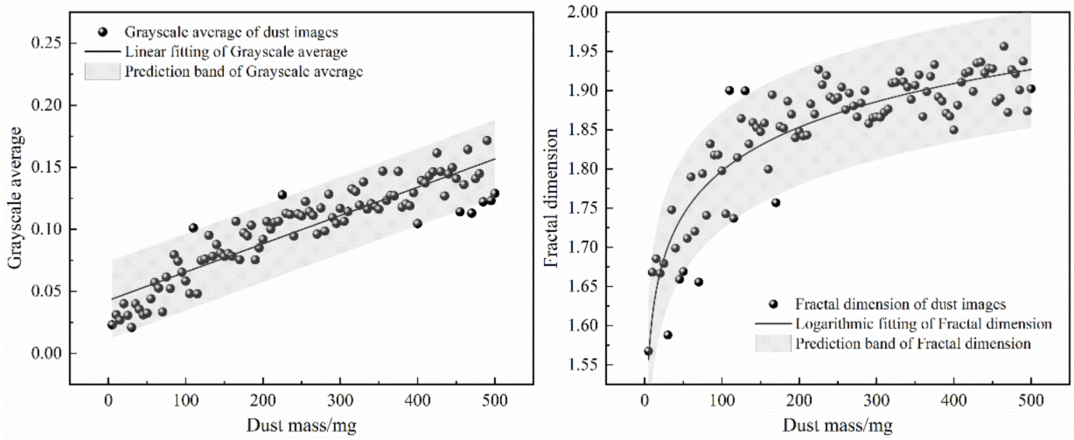


FIG 2 – Experimental dust images with the image processing results for 100 mg dust samples.

The analysis primarily focused on the determination of grey scale averages for different dust samples, providing crucial quantitative data regarding the distribution and intensity of dust dispersion. Linear fitting techniques were subsequently employed to establish a robust relationship between grey scale average results and dust mass, thereby facilitating a deeper understanding of the factors influencing dust dispersion dynamics. Notably, outlier detection methodologies were employed to ensure the accuracy and reliability of the derived relationships, mitigating the impact of anomalous data points on the overall analysis.

Similarly, the fractal dimension of the dust samples was rigorously analysed, with outliers systematically removed to enhance the accuracy of the derived results. Utilising logarithmic fitting techniques, the relationship between fractal dimension and dust mass was elucidated, providing valuable insights into dust particles' complex spatial distribution patterns within the experimental environment. The calculation results after the outlier removal of the grey scale average and fractal dimension are presented in Figure 3.



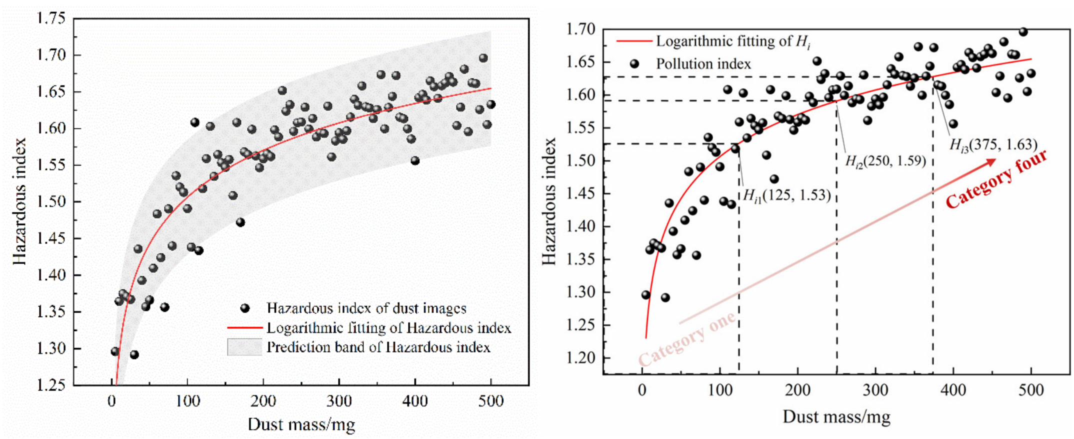
(a) (b)

FIG 3 – The grey scale average and fractal dimension results of dust images, along with the fitting results: (a) Grey scale average of dust images; (b) Fractal dimension of dust images (data from Yin *et al*, 2023; Wang, Yin and Zhou, 2024).

Development of hazardous index

Building upon the insights gleaned from the analysis of dust images, a novel approach for assessing dust pollution levels was proposed through the development of a hazardous index. This index ingeniously integrated key parameters such as grey scale average and fractal dimension, leveraging their respective relationships with dust mass to establish a comprehensive classification system.

By categorising dust images into four distinct groups based on dust mass, the hazardous index provided a reliable framework for assessing the severity of dust pollution within the experimental environment. Notably, the index demonstrated a logarithmic correlation with dust mass, enabling accurate classification and characterisation of dust pollution levels across varying experimental conditions. The hazardous index results and relevant classification criteria of the DL data set are denoted in Figure 4.



(a) (b)

FIG 4 – Hazardous index results for preparing the DL data set, including (a) the hazardous index of the dust image consisting of homologous regressive analysis, and (b) the classification criteria for preparing the DL data set (data from Yin *et al*, 2023; Wang, Yin and Zhou, 2024).

Deep learning model for classification

In a bid to further enhance the efficiency and accuracy of dust pollution assessment, a deep learning model named Inception V3 was developed for classification purposes. Leveraging augmented data sets generated through meticulous data augmentation techniques, the model was trained to classify dust pollution levels with remarkable precision and accuracy. The architecture of the Inception neural network is depicted in Figure 5.

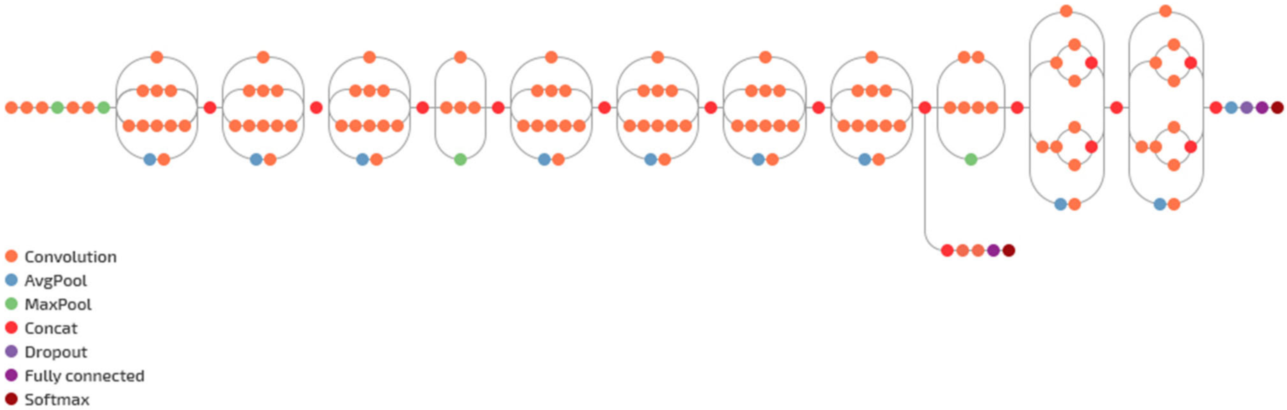
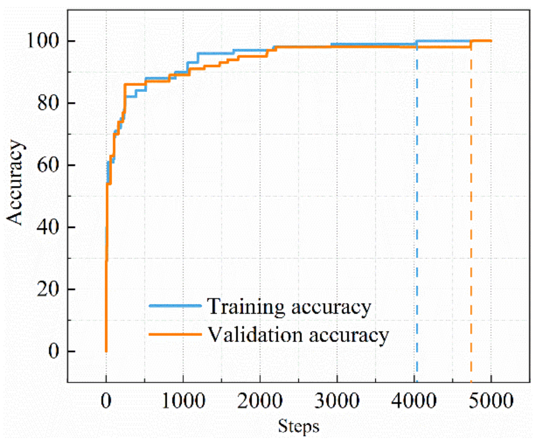


FIG 5 – The network architecture of the Inception V3.

Following model training and validation, the deep learning framework demonstrated exceptional performance, achieving an impressive testing accuracy of 95.3 per cent. The robustness of the model was further validated through the utilisation of precision, recall, and F1-score metrics, which confirmed its reliability in accurately classifying dust pollution levels across diverse experimental conditions.

In essence, the development and implementation of the deep learning model represented a significant advancement in the field of dust pollution assessment, offering a highly efficient and reliable means of classifying and characterising dust pollution levels within mining environments. The model training and testing results are demonstrated in Figure 6.



(a)

Confusion Matrix		Predicted results			
		I	II	III	IV
True results	I	221	3	0	0
	II	1	149	1	3
	III	2	23	156	30
	IV	3	6	16	356

(b)

FIG 6 – The model training and testing results, including (a) training and validation accuracy, and (b) the confusion matrix of the model testing process.

INTEGRATING IMAGE-BASED DUST MONITORING WITH MINING PROCESS OPTIMISATION

The integration of image-based dust monitoring with mining process optimisation represents a significant advancement in enhancing the efficiency, safety, and sustainability of mining operations. By utilising image processing techniques to analyse dust characteristics in real-time, valuable insights can be gleaned to inform strategic decisions regarding mining parameters, ventilation strategies, and dust reduction measures. This integration bridges the gap between dust monitoring and process optimisation by providing insights into rock properties, refining ventilation parameters, and implementing proactive dust control strategies. Future research directions include further refining image processing algorithms, integrating advanced machine learning techniques, and evaluating the long-term effectiveness of integrated monitoring systems in diverse mining environments. Ultimately, this approach contributes to the development of innovative solutions for mitigating dust pollution and improving environmental sustainability in the mining industry. The schematic diagram of the proposed system for dust monitoring and process optimisation in mining operations is depicted in Figure 7.

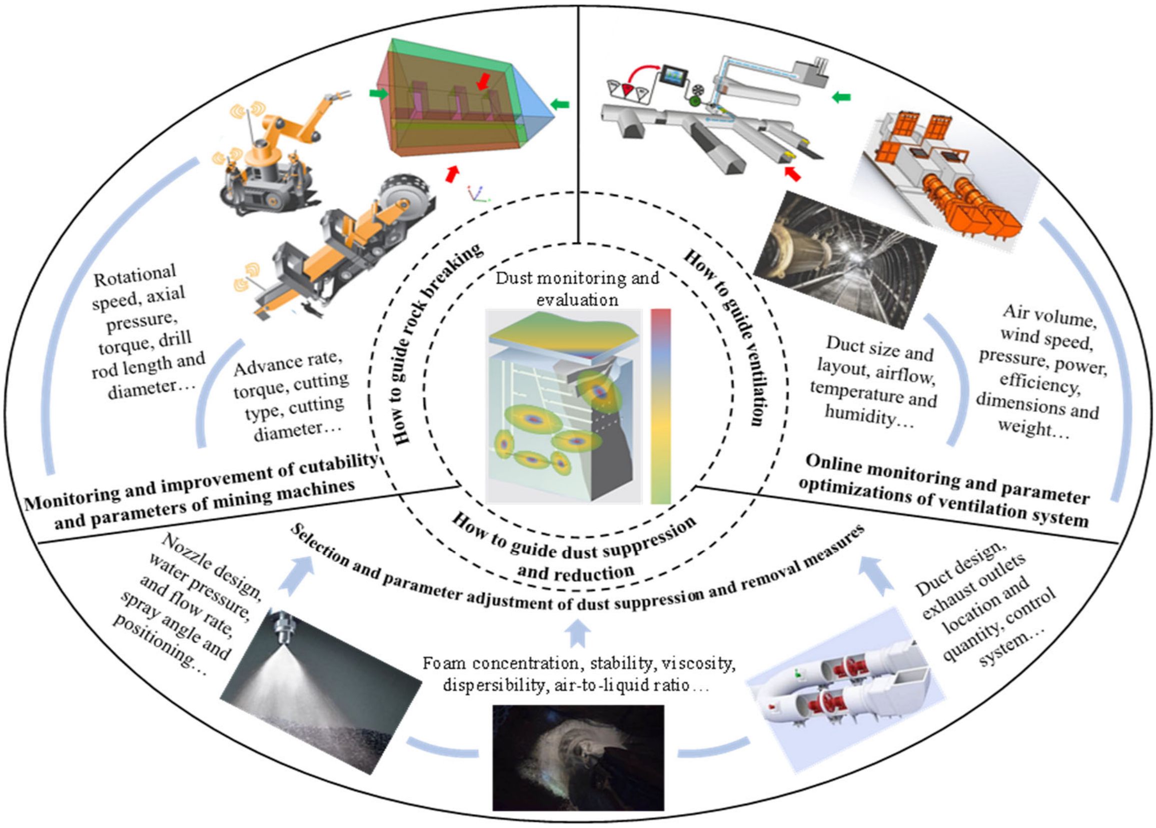


FIG 7 – Diagram of the proposed image processing system for dust monitoring and process optimisation in mining operations, including the excavation system, ventilation system, and dust reduction system.

CONCLUSIONS

In conclusion, this study has presented a comprehensive approach for analysing dust pollution in mining environments through the integration of digital image processing and deep learning techniques. By meticulously simulating dust dispersion and capturing high-resolution images, valuable insights into dust characteristics and behaviour have been gained. The analysis of dust images has enabled the extraction of key parameters, facilitating the development of a novel hazardous index for assessing pollution levels with remarkable precision. Moreover, the implementation of a deep learning model has further enhanced the accuracy and efficiency of dust pollution assessment, achieving exceptional performance in classification tasks. Importantly, the integration of image-based dust monitoring with mining process optimisation represents a significant advancement in enhancing the efficiency, safety, and sustainability of mining operations. This approach enables informed decision-making regarding mining parameters, ventilation strategies, and dust reduction measures by providing real-time insights into dust characteristics. Future research directions include refining image processing algorithms, integrating advanced machine learning techniques, and evaluating the long-term effectiveness of integrated monitoring systems in diverse mining environments. Ultimately, this research contributes to the development of innovative solutions for mitigating dust pollution and improving environmental sustainability in the mining industry.

ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Foundation of China (No. 52174099), the Science and Technology Innovation Program of Hunan Province (2023RC3050), and the Fundamental Research Funds for the Central Universities of Central South University (No. 2024ZZTS0009), for which the authors are very thankful.

REFERENCES

Abbasi, B, Wang, X, Chow, J C, Watson, J G, Peik, B, Nasiri, V, Riemenschnitter, K B and Elahifard, M, 2021. Review of respirable coal mine dust characterization for mass concentration, size distribution and chemical composition, *Minerals*, 11(4):426.

Albatayneh, O, Forsl¨of, L and Ksaibati, K, 2019. Developing and validating an image processing algorithm for evaluating gravel road dust, *Int J Pavement Res Technol*, 12(3):288–296.

Alvarado, M, Gonzalez, F, Fletcher, A and Doshi, A, 2015. Towards the development of a low cost airborne sensing system to monitor dust particles after blasting at open-pit mine sites, *Sensors*, 15(8):19667–19687.

Fan, L and Liu, S, 2021. Respirable nano-particulate generations and their pathogenesis in mining workplaces: a review, *International Journal of Coal Science and Technology*, 8(2):179–198.

Fu, Y and Wang, N, 2013. Measurement of dust concentration based on VBAI, *J Phys Conf*, 418:12079.

Grasa, G and Abanades, J C, 2001. A calibration procedure to obtain solid concentrations from digital images of bulk powders, *Powder Technol*, 114(1):125–128.

Ji, X, Yao, Y and Long, X, 2018. What causes PM2.5 pollution? Cross-economy empirical analysis from socioeconomic perspective, *Energy Policy*, 119:458–472.

Li, G, Wu, J, Luo, Z and Chen, X, 2019. Vision-based measurement of dust concentration by image transmission, *IEEE Instrum Meas*, 68(10):3942–3949.

Trechera, P, Querol, X, Lah, R, Johnson, D, Wrana, A and Williamson, B, 2022. Chemistry and particle size distribution of respirable coal dust in underground mines in Central Eastern Europe, *International Journal of Coal Science and Technology*, 9.

Wang, S, Yin, J and Zhou, Z, 2024. A comprehensive evaluation method for dust pollution: digital image processing and deep learning approach, *Journal of Hazardous Materials*, 134761.

Wang, S, Yin, J, Liang, Y and Tian, F, 2022a. Dust pollution evaluation based on grayscale average and fractal dimension of digital image, *J Clean Prod*, 134691.

Wang, Z, Zhou, W, Jiskani, I M, Luo, H, Ao, Z and Mvula, E M, 2022b. Annual dust pollution characteristics and its prevention and control for environmental protection in surface mines, *Science of The Total Environment,* 825:153949.

Yin, J, Lei, J, Fan, K and Wang, S, 2023. Integrating image processing and deep learning for effective analysis and classification of dust pollution in mining processes, *International Journal of Coal Science and Technology*, 10(1).

Zaid, M M, Amoah, N, Kakoria, A, Wang, Y and Xu, G, 2024. Advancing occupational health in mining: investigating low-cost sensors suitability for improved coal dust exposure monitoring, *Measurement Science and Technology,* 35(2):25128.

Lithology classification through machine learning models – assessing and enhancing the generalisability of single boreholes in north-western Bowen Basin, Australia

Z Yu[1], G Si[2], K Tang[3], V Salamakha[4], J Oh[5] and X Wu[6]

1. PhD Candidate, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: zexin.yu@student.unsw.edu.au
2. Associate Professor, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: g.si@unsw.edu.au
3. Postdoctoral Research Fellow, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: kunning.tang@unsw.edu.au
4. Undergraduate, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: v.salamakha@student.unsw.edu.au
5. Associate Professor, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: joung.oh@unsw.edu.au
6. Mphil Candidate, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: xuebin.wu1@student.unsw.edu.au

ABSTRACT

The development of machine learning (ML) algorithms has led to promising advances in lithology classification from geophysical logs, which is indispensable in various underground engineering applications. Due to the resolution and availability of logging data, ML models can recognise lithology change in a definitive form at a fine scale (0.01 m). While the results from previous models indicated promising performance in the classification, the robust capability of generalising lithology prediction to unseen data may not be true for those models due to: (1) data bias caused by borehole selections, and (2) logging data mismatches among boreholes. To this end, this paper aims to investigate the generalisability of ML models and seek potential improvements. Four ML models were selected to be trained on single reference boreholes to test the other (as unseen) in the same region, which includes Support Vector Classifier (SVC), Random Forest (RF), eXtreme Gradient Boosting (XGBoost) and Residual Neural Network (ResNet10). The data set involves 11 boreholes from a coalmine in north-western Bowen Basin (Queensland, Australia): density, gamma ray, neutron, and sonic logs are selected as inputs. Additionally, a data adaptation method is applied for better generalisability. The results show that there is an accuracy trade-off between the same borehole and unseen boreholes across the models. It also indicates a 16–43 per cent reduction in model performance when generalising the predictions (in marco-F1 score), while the adapted data sets can contribute to a around 12 per cent improvement. This study provides a fundamental understanding of the model generalisability when using a single borehole, essential for further correlating boreholes for regional lithology classification; the adaptation method can improve the generalised accuracy, and reduces the labour to label lithology, which facilitates the identification of gas storage mechanisms, geological/geophysical modelling, and stratigraphic analysis.

INTRODUCTION

Lithology identification is essential for various underground engineering practices, including civil, mining, geo-energy exploration, storage and environmental management. The conventional process relies on log images, manual interpretation of geophysical logs, and laboratory analysis of drill core samples (Newell *et al*, 2021; Saporetti, Da Fonseca and Pereira, 2019; Xu *et al*, 2022). However, it is labour-intensive, costly, and time-consuming, highlighting the need for automated and accurate methods, which is been increasingly advanced by the rise of machine learning (ML). Prominent models include Support Vector Machines (SVMs), tree-based methods, and Artificial Neural Networks (ANNs) (Al-Anazi and Gates, 2010; Alzubaidi *et al*, 2021; Harris and Grunsky, 2015); these models achieve high accuracy, wherein the use of geophysical logs has been extensive. However, generalising trained models to new unseen data remains a challenge due to data variance among boreholes (Shier, 2004) – log readings from adjacent boreholes may not match even within the same geological units. The geophysical logging data is thus transformed to address such an issue. Simple ones like z-score and min-max scaling can help (Kumar, Seelam and Rao, 2022; Lin *et al*, 2021), while they may not result in optimal generalised identifications due to the data's nature of non-Gaussian distributions and varying ranges. More complex methods can be non-intuitive and computationally intensive (Kadkhodaie and Rezaee, 2017; Karimi, Sadeghnejad and Rezghi, 2021).

This study aims to investigate ML models' generalisability trained on single boreholes, focusing on the impact of borehole selections and log reading mismatches. The data set includes four geophysical logs (density, gamma ray, neutron, sonic) from 11 boreholes in a coalmine of Bowen Basin, Queensland, Australia, wherein the main lithologies are characterised by sandstone, siltstone, coal, and tuff. Four ML models were tested including Support Vector Classifier (SVC), Random Forest (RF), eXtreme Gradient Boosting (XGBoost), and Residual Neural Network (ResNet10). Each model was trained on a single reference borehole and tested on the others. BH1, BH2, BH7, and BH10 were randomly selected as references considering borehole selections, resulting in 16 different ML models. A data adaptation method was introduced to address the mismatches, consequently, to improve the generalisability. Model performance was assessed using multiclass confusion matrices, macro-F1 scores.

METHODS

An ML-based workflow was used to identify the four primary lithologies in all studied boreholes, shown in Figure 1. Raw data was extracted, and a pilot training process on BH1 identified significant features. Each reference borehole was then used to train ML models with optimal parameters. These models were tested on the other ten boreholes, varying iteratively by reference borehole. Generalisability was examined using a data adaptation method. The process included data processing, model training, data adaptation, inference, and comparative analysis of generalisability and performance.

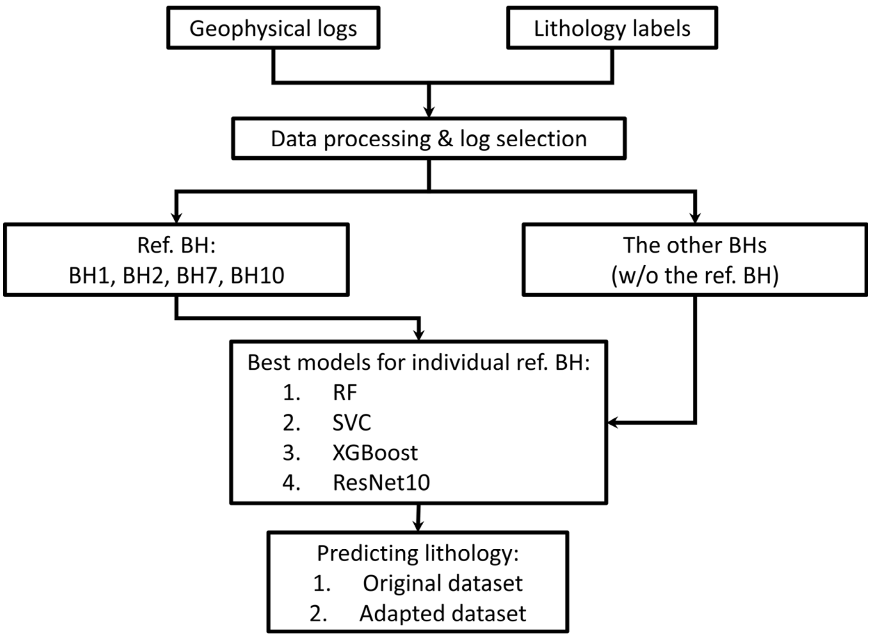


FIG 1 – ML workflow to identify lithologies using geophysical logs.

Materials and machine learning models

The study area is located in the north-western section of the NNW-SSE trending platforms of Bowen Basin, which consists of the Moranbah Coal Measures, Fair Hill Formation, and Platypus Tuff Bed. Primary lithologies are volcano-lithic sandstone, siltstones, coal, and tuff, denoted as SS, ST, C, and TF. Geophysical logging and lithology data of 11 boreholes were collected from a coalmine in this area (seen Figure 2), coded as BH1-BH11. Star markers were the randomly selected as the reference boreholes. When the reference borehole is fed to train and validate ML models, the other 10 boreholes are used as unseen ones to test. The four geophysical logs applied are outlined in Table 1, where their extreme values among boreholes were evaluated by coefficients of variation

(Brown, 1998). The logs were scaled to [0, 1] and then matched with lithology labels based on the logging depth step at 0.01 m.

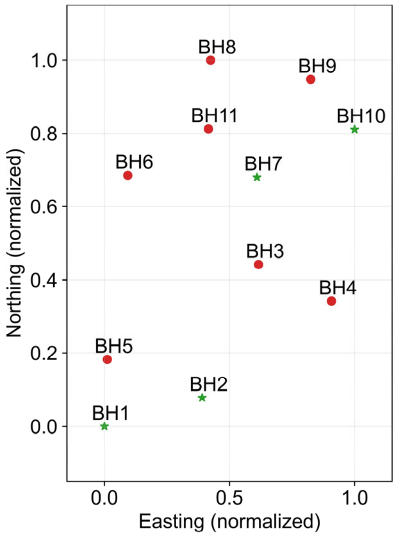


FIG 2 – Borehole locations with distance normalised: reference boreholes (orange triangular) for model training and the remaining (blue points) for the prediction.

TABLE 1

Geophysical logs applied and respective coefficient of variation for extreme readings.

Logs	**Unit**	**CV**	
		Min	**Max**
DEPT	**m**	**-**	**-**
Gamma ray	GAPI	32.99%	8.93%
Density	g/c^3	61.71%	2.78%
Sonic	μs/m	1.76%	5.95%
Neutron	SNU	6.60%	9.85%

The ML models applied for the lithology identification are RF (Breiman, 2001), SVM (Vapnik, 1999), XGBoost (Chen and Guestrin, 2016), and light-implementation of Residual Neural Network, ResNet10 (He *et al*, 2016), which can represent the generalised performance from different ML approaches:

1. RF is an ensemble method that constructs multiple independent decision trees and derives predictions through collective voting. It is relatively accurate for classification tasks, resistant to anomalous log responses, and requires minimal preprocessing. It provides feature importance, aiding in understanding the underlying data.
2. SVM is a robust supervised ML model for classification (denoted as SVC), distinguishing classes by forming hyperplanes. It performs well with limited data without needing to know the underlying distribution.
3. XGBoost is an optimised gradient-boosting decision tree algorithm that sequentially combines weak learners for robust predictions. It provides feature importance, is less sensitive to anomalous log readings, and includes regularisation methods to prevent overfitting, enhancing generalisability.
4. ResNet10 is employed for its ability to extract high-dimensional features. Its architecture is less sensitive to initial parameter settings, contributing to good generalisability.

Multiclass confusion matrices were used to evaluate the result of each borehole, and macro-F1 scores was the matrices for overall assessment, which ensured that CO and TF were not over-represented by SS and ST.

Data adaptation and comparative analysis

Since the formations in the borehole location is consistent, it can be expected the log readings with lithologies follow similar distribution shapes. Therefore, a data adaptation method is introduced on the original scaled data sets to improve the identification on unseen data, shown in Figure 3. The method includes two steps: quantile mapping and linear fitting. Twenty-one quantiles (incremented by 5, ie 0th, 5th, 10th… 100th) were used to extract values from all logs of the 11 boreholes; the first and the last were removed to suppress the effect of varying outliers, termed as Linear21. Each reference borehole's quantiles were paired with those of the remaining boreholes and underwent linear fitting. By this adaptation, lithology distribution patterns in the other boreholes can align more closely with that in the reference for better generalisability without knowing the prior knowledge. The adapted data set is also transferrable to the original.

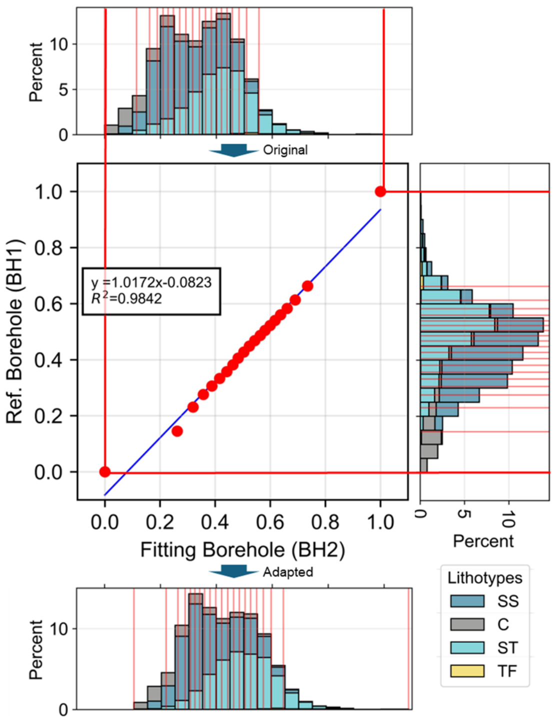


FIG 3 – Data adaptation of gamma ray between the fitting borehole (BH2) and the reference borehole (BH1): quantiles (red) of BH2 extracted to fit that of BH1 via linear regression (blue).

The data sets from each reference borehole were split into 80 per cent for training and 20 per cent for validation. Four ML models—RF, SVC, XGBoost, and ResNet10—were implemented with a typical training workflow that involved training and parameter tuning. Hyperparameters were tailored to specific data sets corresponding to the reference boreholes, resulting in a total of 16 different models. Model performance was evaluated using confusion matrices and macro-F1 scores. The remaining boreholes in each iteration served as the testing set to assess generalisability. The effectiveness of Linear21 was also examined.

RESULTS AND DISCUSSION

Confusion matrices were produced to present the model's performance on the validation sets corresponding to each reference borehole, as shown in Figure 4a. The models trained by the tree-based methods outperformed SVC and ResNet10 with higher accuracy in the validation data set of this study, wherein XGBoost consistently delivers the highest overall accuracy for all classes across all reference boreholes. Although tuff was misclassified in the model trained using BH10's data set, RF also demonstrated comparable accuracy in those cases. ResNet10 models offer fair accuracy in all the references, where most predictions fall within the diagonal axis of the matrices. On the contrary, SVC appears to undergo difficulties in learning features for different reference boreholes, resulting in significant performance variability. In terms of specific lithology classes, almost all ML models can identify coal with more than 90 per cent accuracy, as coal's properties distinctly vary from other lithotypes' in the logs. For both SS and ST, RF, XGBoost, and ResNet10 exhibit fair prediction accuracy of around 80 per cent. When misclassified, the two lithologies were prone to be wrongly labelled as each other. This can be caused by the overlapping ranges in their log readings, which hinders the models from differentiating. Classification accuracy on tuff can achieve more than 90 per cent, while the lithology was mistakenly identified as C in most false instances. This suggests that the inter-bedded layers can confuse the ML models to recognise the class with a smaller proportion. Besides, the challenges of human error are also inevitable when the properties of lithologies are close or when the stratigraphy features multiple thin layers inter-bedded (Horrocks, Holden and Wedge, 2015). The models trained on BH1 and BH2 presents favourable lithology prediction performance, whereas those models trained on BH7 and BH10 struggled to classify non-coal lithotypes. We then applied the trained models on the testing sets in accordance with respective references and obtained Figure 4b. The classification performance of the models generally undergoes a significant attenuation when predicting the lithologies in unseen boreholes. As a result, peak scores can be found around the reference boreholes. Except on BH10, the models trained on the other references have difficulties in classifying the labels in BH10 and BH11. However, those trained on BH10 perform consistently bad with all the testing sets, meaning that the data bias due to borehole selections cannot be ignored under current circumstances. Although the scores for validation sets are lower than the tree-based models, in SVC and ResNet10, the generalised results from different reference boreholes are closer with one another. These patterns indicate that choosing a different borehole as a starting reference might be less impactful to these models' learning. Furthermore, while the general trend of scores decreases as the relative distance, their irregular fluctuations leave uncertainty on such observations.

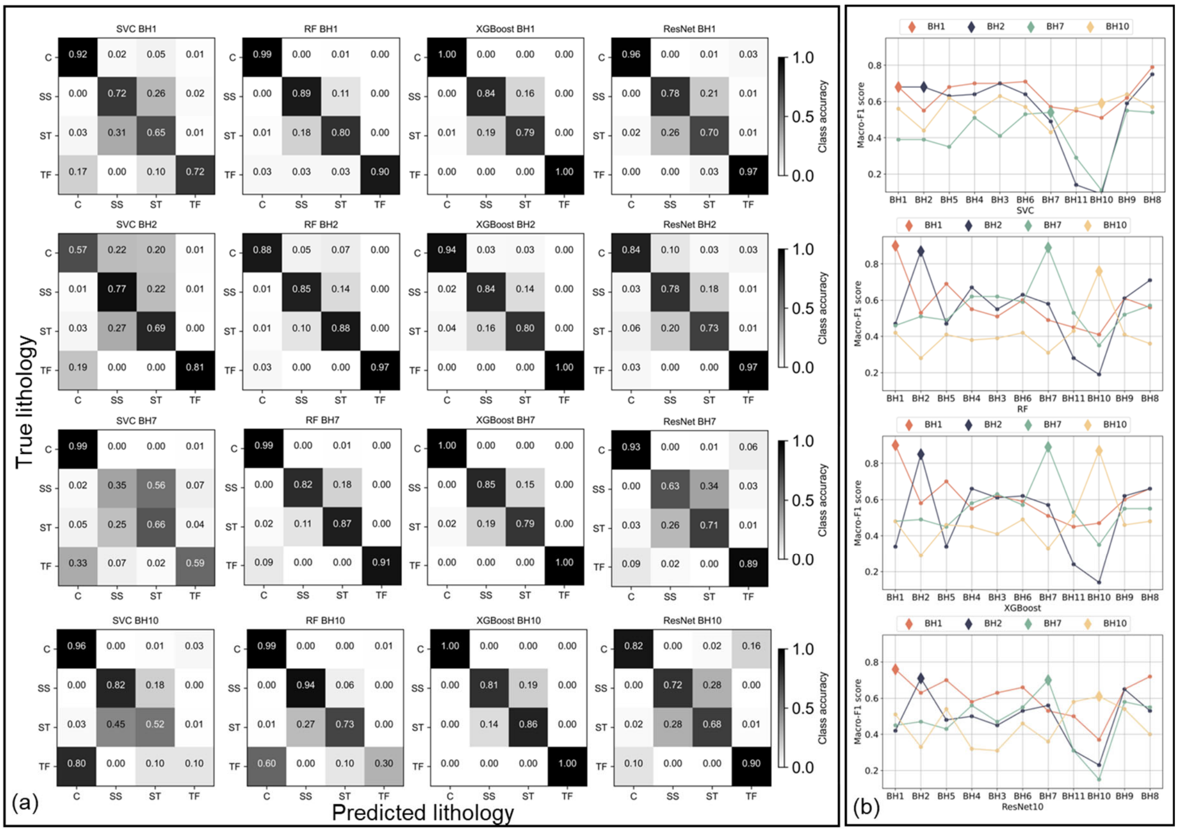


FIG 4 – Trained models with the original data: (a) Normalised confusion matrices of the 16 ML models with SVC, RF, XGBoost, and ResNet10 trained on the reference boreholes: BH1, BH2, BH7, and BH10, (b) impact of reference borehole selections: macro-F1 scores for both the references (triangular markers) and respective generalised boreholes (dot markers and lines in the same colours), arranged by ascending relative distance from BH1.

When applying the original data on the trained models, the generalised results presenting various macro-F1 scores suggest that the standard feature engineering approach adopted was not enough to tackle the data mismatches. The trained models were then subjected to test the unseen boreholes with the original and adapted data sets. The results are shown in Figure 5. In Figure 5a, the score elevation is evident when comparing Linear21 with the Original, where each model includes 40 result points. Few cases fall on the upper left side of the diagonal with all the other remaining borehole combinations: 22.5 per cent of the cases for SVC, 7.5 per cent for RF, 2.5 per cent cases for XGBoost, and 7.5 per cent cases for ResNet10. Detail counts on models trained by each reference borehole are tabulated in Table 2, where the three different improvement criteria are defined by:

- Fair case: score difference between Original and Linear21 stays within ±0.01.
- Worse case: a drop in scores exceeds 0.01 after applying Linear21.
- Better case: an increase in scores exceeds 0.01 after applying Linear21.

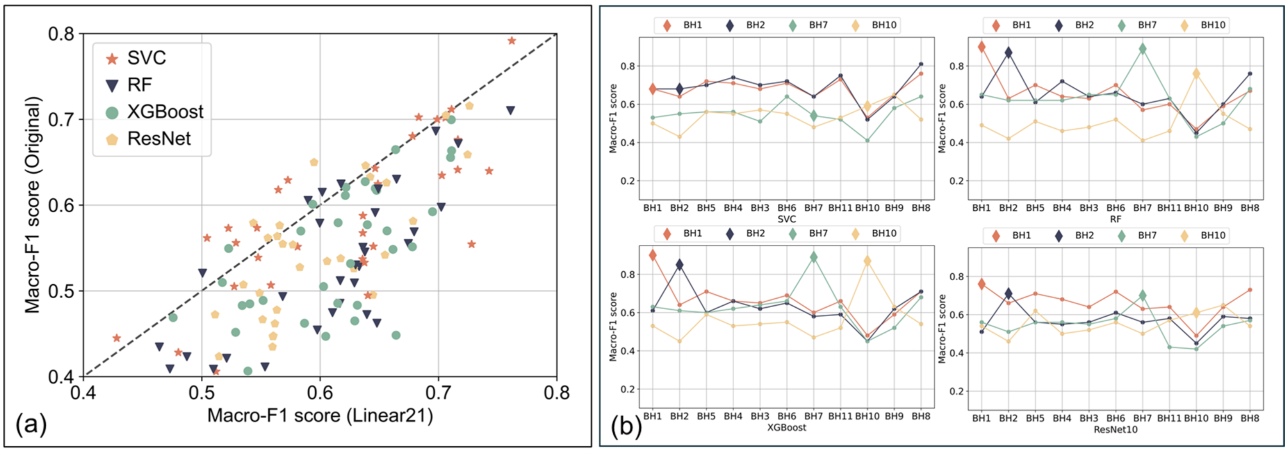


FIG 5 – Effects of data adaptation across all borehole groups: (a) performance improvement by Linear21 compared to the Original, (b) impact of reference borehole selections after Linear21: macro-F1 scores for both the references (triangular markers) and respective generalised boreholes (dot markers and lines in the same colours), arranged by ascending relative distance from BH1.

TABLE 2

Borehole-wise case count for generalised results between original and adapted data sets.

Models by ref BH	BH1	BH2	BH7	BH10	Total
Worse	3	2	3	8	16
Fair	9	7	3	4	23
Better	28	31	34	28	121
Total	40	40	40	40	160

Plotting the results in Figure 5b, it can also be observed that the generalised results from different reference boreholes are closer to each other compared with Figure 4b, suggesting the robustness to the impact of borehole selections. As a result, Linear21 can typically be used to aid generalised classifications.

Figure 6 presents a comparative analysis of the classification performance across four ML models. Red bars indicate the average macro-F1 scores from combination of all other boreholes (when not fed to train), remaining original and processed by Linear21, respectively. Error bars reflect the standard deviation of these data. In terms of validation sets from reference boreholes, XGBoost outstands with the highest mean score and the smallest variation, followed by the other tree-based model, RF, scoring 0.86. In contrast, the deep neural network, ResNet10, scores lower at 0.69, underperforming in both average score and variability compared to the other models. SVC models, though scoring lower at 0.62 for macro-F1, show less performance degradation in generalised classification tasks. The decrease in performance observed across the models—SVC, RF, XGBoost, and ResNet10—results in scores dropping to around 0.5. The adaptations to the data sets improve this decline to around 0.6, which accounts for about 13 per cent, 10 per cent, 11 per cent, and 12 per cent improvement. While all four ML models show a consistent drop in scores when dealing with unseen lithologies using the original data set, the introduction of the Linear21 method mitigates this effect, thereby indicating improved generalisability after data adaptation.

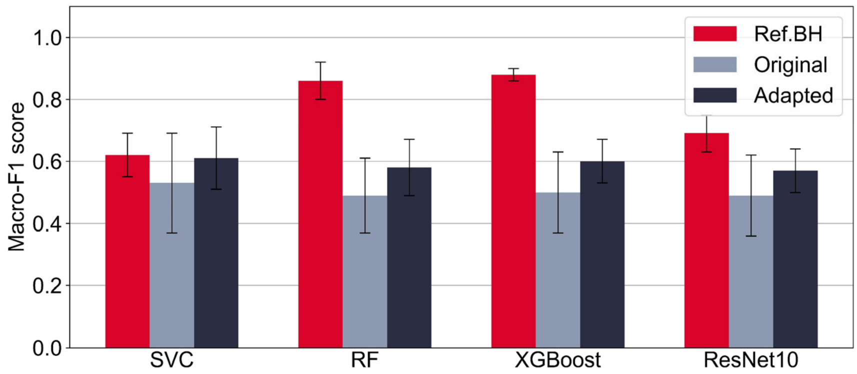


FIG 6 – Model-wise scores across data sets including validation sets in reference boreholes (red), direct predictions on the testing sets (grey), and the adapted testing sets (black).

CONCLUSIONS

The extent to which a single borehole correlates with the other ones is fundamental to lithology composition in an area. This study has systematically explored ML models' generalisability by training on single reference boreholes to test the unseen within a coalmine in Australia. The involved formation covers parts of Moranbah Coal Measures with its unique tuffaceous layers, resulting in four major lithologies to be classified: sandstone, siltstone, coal, and tuff. Four types of geophysical logs from 11 boreholes (BH1-BH11). Four types of popular ML algorithms (SVC, RF, XGBoost, ResNet10) trained on four randomly selected reference boreholes (BH1, BH2, BH7, BH10) forms a total of 16 models for a comparative analysis on constraints of the algorithms and data, log reading mismatches across boreholes. The findings are summarised as:

- For borehole-wise classification, the tree-based methods outperformed in borehole-wise classification. RF and XGBoost achieved an average Macro-F1 over 0.85 on the reference boreholes, while the average score for ResNet10 is 0.69, slightly better than SVC being 0.62.
- The data bias by borehole selections cannot be ignored. ResNet10 and SVC are more robust than tree-based models on different reference boreholes when generalising results in unseen boreholes.
- A data adaptation method alleviating data mismatches can contribute to around 10–12 per cent less attenuation when generalising results compared with the original data sets.

This study applies ML models to evaluate the generalisability of single boreholes in a restricted area, which is fundamental to multi-borehole correlation for a regional lithology classification. It supports the automation of lithology classification with less labour cost and environmental impacts. Consequently, the next stage involves calibrating multiple boreholes' geophysical logs to optimise results for mapping regional lithology compositions. Moreover, it is essential to explore methods that incorporate a broader range of geophysical logs without introducing additional imbalances into the data sets. A further step includes refining the quantile selections for the data adaptation method to enhance consistency in log readings and improve classification accuracy.

ACKNOWLEDGEMENTS

The work reported here is funded by the Australian Coal Industry's Research Program (ACARP), Grant no. C33018.

REFERENCES

Al-Anazi, A and Gates, I D, 2010. A support vector machine algorithm to classify lithofacies and model permeability in heterogeneous reservoirs, *Engineering Geology*, 114(3–4):267–277.

Alzubaidi, F, Mostaghimi, P, Swietojanski, P, Clark, S R and Armstrong, R T, 2021. Automated lithology classification from drill core images using convolutional neural networks, *Journal of Petroleum Science and Engineering*, 197:107933.

Breiman, L, 2001. Random Forests, *Machine Learning*, 45(1):5–32.

Brown, C E, 1998. Coefficient of Variation, in *Applied Multivariate Statistics in Geohydrology and Related Sciences* (ed: C E Brown), pp 155–157 (Springer: Berlin Heidelberg).

Chen, T and Guestrin, C, 2016. XGBoost: A Scalable Tree Boosting System, in *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, pp 785–794.

Harris, J R and Grunsky, E C, 2015. Predictive lithological mapping of Canada's North using Random Forest classification applied to geophysical and geochemical data, *Computers and Geosciences*, 80:9–25.

He, K, Zhang, X, Ren, S and Sun, J, 2016. *Deep residual learning for image recognition,* pp 770–778.

Horrocks, T, Holden, E-J and Wedge, D, 2015. Evaluation of automated lithology classification architectures using highly-sampled wireline logs for coal exploration, *Computers and Geosciences*, 83:209–218.

Kadkhodaie, A and Rezaee, R, 2017. Intelligent sequence stratigraphy through a wavelet-based decomposition of well log data, *Journal of Natural Gas Science and Engineering*, 40:38–50.

Karimi, A M, Sadeghnejad, S and Rezghi, M, 2021. Well-to-well correlation and identifying lithological boundaries by principal component analysis of well-logs, *Computers and Geosciences*, 157:104942.

Kumar, T, Seelam, N K and Rao, G S, 2022. Lithology prediction from well log data using machine learning techniques: A case study from Talcher coalfield, Eastern India, *Journal of Applied Geophysics*, 199:104605.

Lin, J, Li, H, Liu, N, Gao, J and Li, Z, 2021. Automatic Lithology Identification by Applying LSTM to Logging Data: A Case Study in X Tight Rock Reservoirs, *IEEE Geoscience and Remote Sensing Letters*, 18(8):1361–1365. https://doi.org/10.1109/LGRS.2020.3001282

Newell, A J, Woods, M A, Graham, R L and Christodoulou, V, 2021. Derivation of lithofacies from geophysical logs: A review of methods from manual picking to machine learning (National Geoscience Programme), British Geological Survey.

Saporetti, C M, Da Fonseca, L G and Pereira, E, 2019. A Lithology Identification Approach Based on Machine Learning With Evolutionary Parameter Tuning, *IEEE Geoscience and Remote Sensing Letters*, 16(12):1819–1823.

Shier, D E, 2004. Well Log Normalization: Methods and Guidelines, *Petrophysics – The SPWLA Journal of Formation Evaluation and Reservoir Description*, 45(03):13.

Vapnik, V, 1999. *The Nature of Statistical Learning Theory* (Springer Science and Business Media).

Xu, Z, Ma, W, Lin, P and Hua, Y, 2022. Deep learning of rock microscopic images for intelligent lithology identification: Neural network comparison and selection, *Journal of Rock Mechanics and Geotechnical Engineering*, 14(4):1140–1152.

Vibration energy harvesting for self-powered sensors at mine sites

H Zhang[1], B Li[2], M Karimi[3], M Hassan[4] and S Saydam[5]

1. UNSW, Sydney NSW 2052. Email: huili.zhang@unsw.edu.au
2. Associate Professor, UNSW, Sydney NSW 2052. Email: binghao.li@unsw.edu.au
3. UTS, Sydney NSW 2007. Email: mahmoud.karimi@uts.edu.au
4. Professor, UNSW, Sydney NSW 2052. Email: mahbub.hassan@unsw.edu.au
5. Professor, UNSW, Sydney NSW 2052. Email: s.saydam@unsw.edu.au

ABSTRACT

With the prevalence of Mine Internet of Things (MIoT), different types of sensors have been widely deployed in mine sites for environmental monitoring and operational management. Currently, sensors in mine sites are mainly powered by cables or batteries. However, the deployment and maintenance of a power supply network can be difficult and expensive, and batteries have a limited lifespan. The vibration energy harvesting (VEH) technology can be used to provide power for low-power sensors in mine sites. This presentation briefly introduces three widely used VEH methods (ie piezoelectric, electromagnetic, and electrostatic). The performance of a commercial electromagnetic energy harvester (ReVibe model D) is evaluated based on the vibration of a lab vibrator (3 g, 50 Hz) and an idling SUV automobile (0.3 g, 25 Hz). Experimental results indicate that a ReVibe energy harvester can generate adequate electricity to power a sensor, and its power output depends on the load resistance as well as the vibration frequency and amplitude of vibration sources. To apply VEH to mining applications, this study also analyses the characteristics of vibration sources at the mine site based on the vibration data collected from various operating machines in a coal handling and preparation plant (CHPP). The vibration analysis results indicate that all the measured vibration sources in the CHPP can generate stable and abundant vibrations, characterised by substantial amplitudes (up to 5.55 g) and low dominant frequencies (ranging from 14 Hz to 25 Hz), which are sufficient for VEH.

INTRODUCTION

The Industrial Internet of Things (IIoT) is an interconnected network that enables connectivity and interaction between industrial machines, which is capable of remote monitoring and real-time analysis with minimal human interventions (Sisinni *et al*, 2018). As an important branch of IIoT, Mine Internet of Things (MIoT) has gained increasing attention because it can help improve mining safety and enhance productivity (Molaei *et al*, 2020). The basic structure of MIoT can be depicted by a widely used three-layer architecture, which consists of the perception layer, network layer, and application layer (Yun and Yuxin, 2010). Once the network layer receives the data from sensors deployed in the perception layer, these data will be sent to the application layer for further analysis (Zhou *et al*, 2017). Although the mining industry can greatly benefit from MIoT, the lack of long-term sustainable power supplies for electronics (eg sensors) limits the adoption of IoT systems in mines. Currently, sensors at mine sites are mainly powered by cables or batteries (Jasiulek, Stankiewicz and Woszczyński, 2016). However, as the number of sensors at mine sites has significantly increased, the use of cable-based sensors is not feasible due to the complexity and high cost of sensor deployment and maintenance. Besides, although the advancement of low-power technology has significantly reduced the power consumption of sensors, the battery of a sensor still requires regular replacement, which can be extremely difficult for sensors installed in hard-to-reach areas (Aabid *et al*, 2021).

Energy harvesting is a promising approach for powering standalone low-power sensors, which aims to capture a small amount of wasted energy from the ambient environment (eg heat, radiation, sound, vibration and wind) to power small electronics (eg sensors for MIoT) (Liu *et al*, 2018). Vibration is one of the most ubiquitous energy sources at mine sites because various types of machines continuously operate in mining environments. Therefore, vibrations generated by machines can be harvested to power nearby sensors. Specifically, vibration energy harvesting techniques can be used for developing self-powered sensors at mine sites with the advantages of low cost, long lifetime, flexible, maintenance free, and environmentally friendly (Shirvanimoghaddam *et al*, 2019). To gain a better understanding of the potential of vibration energy harvesting technology for powering sensors deployed in mines, this paper aims to provide an overview of widely used vibration energy harvesting methods, evaluate the performance of a commercial vibration energy harvester, and identify the characteristics of the vibration produced at the mine site based on the vibration data collected from a coal handling and preparation plant (CHPP).

VIBRATION ENERGY HARVESTING METHODS

Three vibration energy harvesting methods, including piezoelectric, electromagnetic, and electrostatic mechanisms, are widely used to convert external vibrations into electricity. Piezoelectric transducers convert mechanical strain into electrical energy using piezoelectric materials, such as ceramic, crystal, polymer and composite, When an external force is applied, an electric field is generated within the piezoelectric layer due to the inhomogeneous distribution of electrical charges (Sezer and Koç, 2021). An electromagnetic energy harvester realises energy scavenge through the interaction of magnets and coils. The relative oscillating motion between the magnet and coil generates induced voltage and current (Sundriyal and Bhattacharya, 2019). Electrostatic transducers operate based on the variation in capacitance, which can result in either a charge increase in a constrained voltage system or a voltage increase in a constrained charge system (Wei and Jing, 2017). Table 1 summarises the advantages and disadvantages of these three vibration energy harvesting techniques. From a practical perspective, electrostatic method is not efficient for vibration energy harvesting at mine sites because of its poor electromechanical behaviour (Le *et al*, 2015).

TABLE 1

Advantages and disadvantages of three vibration energy harvesting methods

Energy harvesting technique	Advantages	Disadvantages
Piezoelectric	• Simple structure and ease of application • Able to be miniaturised • High voltage and high capacitance • High energy density • Little mechanical damping • Less affected by external/internal electromagnetic waves	• Brittle or rigid piezoelectric materials • Toxic piezoelectric materials (eg PZT) • Low output current • Poor coupling in piezo film • Difficult to be fabricated
Electromagnetic	• Low-cost design and possible to operate without contact to the vibrating structure • Easy to be fabricated • High energy density • High output current and low output impedance	• Low output voltage (typically <1 V) • Large space is required • Interfered by electromagnetic waves
Electrostatic	• Scalable • Simple integration • Suitable for capturing low frequencies	• Extremely high output voltage (>100 V) • External voltage sources are required • Not suitable to provide on-site power in practice (high output impedance)

PERFORMANCE OF A COMMERCIAL VIBRATION ENERGY HARVESTER

To evaluate the effectiveness of existing energy harvesters for vibration energy harvesting, a series of experiments were conducted using a commercial electromagnetic energy harvester from ReVibe (model D). It comprises of a spring-connected permanent magnet and a fixed coil within a metal housing. Initially, the performance of the ReVibe energy harvester was examined based on the vibration generated by a lab vibrator. As shown in Figure 1, the energy harvester was placed on a lab vibrator to convert the obtained vibration energy into electrical power. The lab vibrator could produce stable and continuous vibration, characterised by a vibration amplitude of 2 g and a dominant frequency of 50 Hz. A resistive load was connected with the energy harvester to dissipate the generated electricity. An oscilloscope was used to record the generated AC voltage signal. Since generated AC voltage is fluctuant, the Root Mean Square (RMS) value of produced AC voltage is calculated for further analysis. As shown in Figure 2, the RMS load voltage increases as the load resistance increases where RMS load voltage can reach 16.16 V when load resistance rises to 2000 Ω. However, the RMS load power initially increases with the increase of load resistance and then decreases with the increasing load resistance, where the maximum RMS load power (approximately 0.241 W) can be obtained when the load resistance is around 680 Ω.

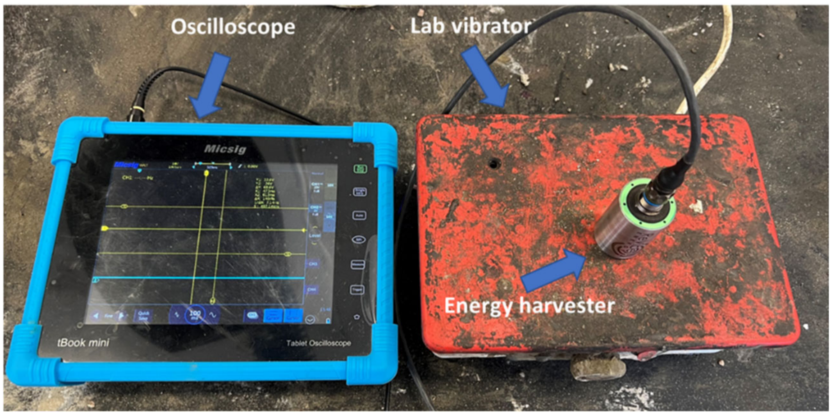


FIG 1 – Experimental set-up for vibration energy harvesting test using ReVibe model D.

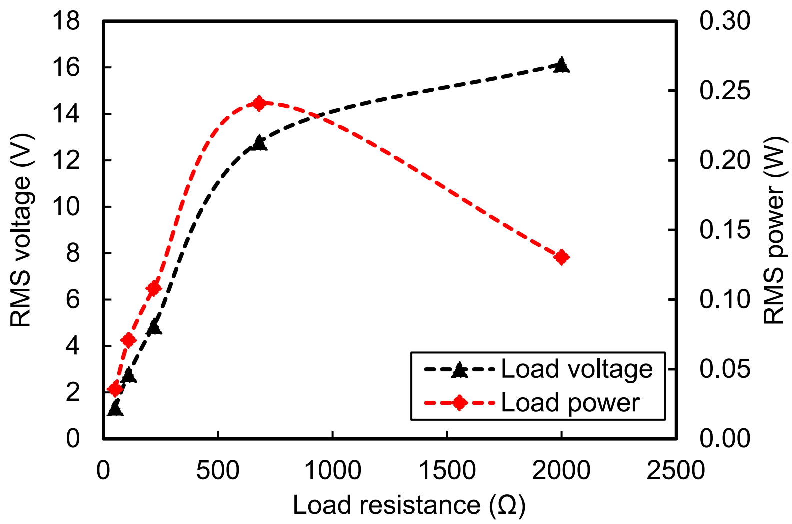


FIG 2 – RMS voltage and power output of the energy harvester attached to a lab vibrator.

Energy harvesting performance test was also conducted based on the vibration generated by an idling SUV automobile. During the experiments, the energy harvester was attached to the car's motor to capture vibration energy. The SUV's motor produced continuous vibrations with a magnitude of 0.3 g and a dominant frequency of 25 Hz. Experimental results indicate that the open-circuit voltage generated by the energy harvester is 114.2 mV. As shown in Figure 3, the RMS load voltage and RMS load power increase with the load resistance. The load voltage increases from 18.24 mV to 92.98 mV when load resistance rises from 51 Ω to 220 Ω, while the load power rises from 6.53 μW to 39.30 μW. Ultimately, load voltage and load power will reach a peak as the load resistance increases. However, despite using the same vibration energy harvester, the energy harvested from an idling SUV automobile is much lower than the energy harvested from the lab vibrator. The output power of the vibration energy harvester attached to the lab vibrator can reach 108 mW with a load resistance of 220 Ω. This difference can be attributed to the vibration amplitudes produced by vibration sources and the deviation between the operating frequency of vibration sources and the resonant frequency of the vibration energy harvester.

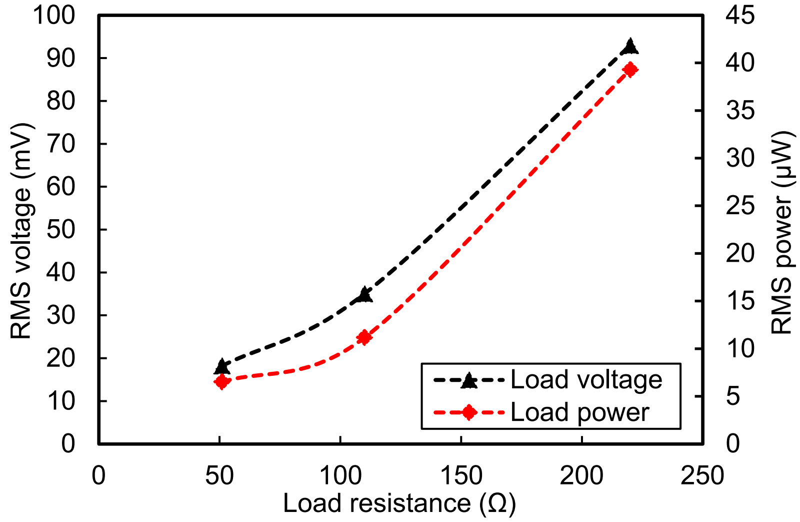


FIG 3 – RMS voltage and power output of the energy harvester attached to an idling SUV automobile.

The power consumed by sensor nodes mainly depends on communication technologies and sleep modes. According to Table 2, with decreasing sleep time, the average power consumption of a Bluetooth Low Energy board embedded with three sensors (TI's CC2650) decreases from 255.3 μW to 693.4 μW, while the average power consumption of a LoRaWAN end-device embedded with four sensors (Pervasive Nation) can be as low as 9.6 μW when the sleep time is 15 mins (Rodriguez, Nico and Punch, 2019). Thus, the commercial ReVibe electromagnetic energy harvester can harvest sufficient power to drive either a Bluetooth Low Energy device or a LoRaWAN device when attached to a lab vibrator. It can also provide adequate electricity for a LoRaWAN device with a sleep time of 5 mins or 15 mins by harnessing vibration energy from an idling SUV automobile.

TABLE 2

Average power consumption of Bluetooth Low Energy board and LoRaWAN board with different sleep time (Rodriguez, Nico and Punch, 2019).

Bluetooth low energy board		LoRaWAN board	
Sleep time	**Power (μW)**	**Sleep time**	**Power (μW)**
0.5 sec	693.4	10 sec	714.5
1 sec	419.6	40 sec	205.9
1.5 sec	328.3	2 min	71.0
2 sec	282.7	5 min	28.7
2.5 sec	255.3	15 min	9.6

VIBRATION ANALYSIS

To identify the characteristics of the vibration produced by operating machines at mine sites, two types of inertial measurement units (IMUs), including the Xsens MTi-680G and the LSM6DSL, were attached to five operating machines and a handrail in a CHPP to collect short-term and long-term vibration data. During the measurement, the short-term vibration data was collected using an Xsens MTi-680G module. The IMU was attached to each vibration source and simultaneously connected to a laptop via the cable for several minutes for data collection and data transmission (Figure 4a). Long-term vibration data was recorded using a LSM6DSL module powered by a lithium battery, which was capable of continuously recording vibration data for a few hours (Figure 4b). By analysing the collected time-history vibration data, the root mean square (RMS) value and the amplitude of the acceleration produced by vibration sources were identified. The dominant operating frequencies and power spectral density (PSD) distribution of each vibration source were determined using a Fast Fourier Transform (FFT).

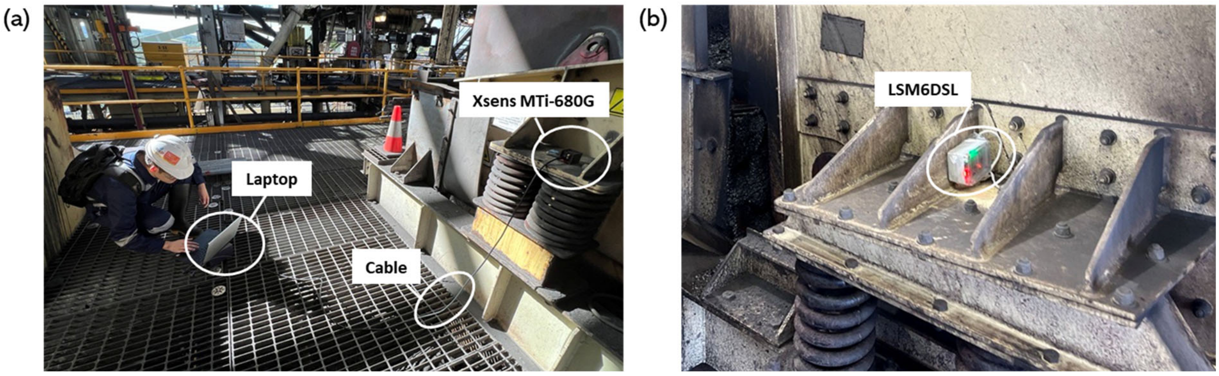


FIG 4 – Vibration data collection at a CHPP: (a) short-term data collection; and (b) long-term data collection.

Short-term vibration data were collected from a handrail and five operating machines including a fine screen, a deslime screen, a clean coal screen, a centrifuge chute, and a centrifuge. Each data collection had a duration of two to three mins with a sampling frequency of 400 Hz. To ensure the data validity, the vibration produced by each vibration source was measured twice. The results of both measurements showed close similarity. Taking the vibration data measured along the y direction of the fine screen as an example, the RMS values of the acceleration for two measurements were 2.402 g and 2.403 g, respectively (Figure 5a and 5b). The dominant frequency in both measurements was almost identical, with a value of 14.1 Hz (Figure 5c and 5d). The maximum power density was 25.87 dB/Hz in the first measurement and 27.55 dB/Hz in the second measurement (Figure 5e and 5f). Similar phenomena were also observed in the x and z directions. Table 3 summarises the vibration characteristics of the five operating machines and the handrail. All the measured vibration sources in CHPP can generate stable and abundant vibrations, characterised by large amplitudes (up to 5.55 g) and low dominant frequencies ranging from 14 Hz to 25 Hz.

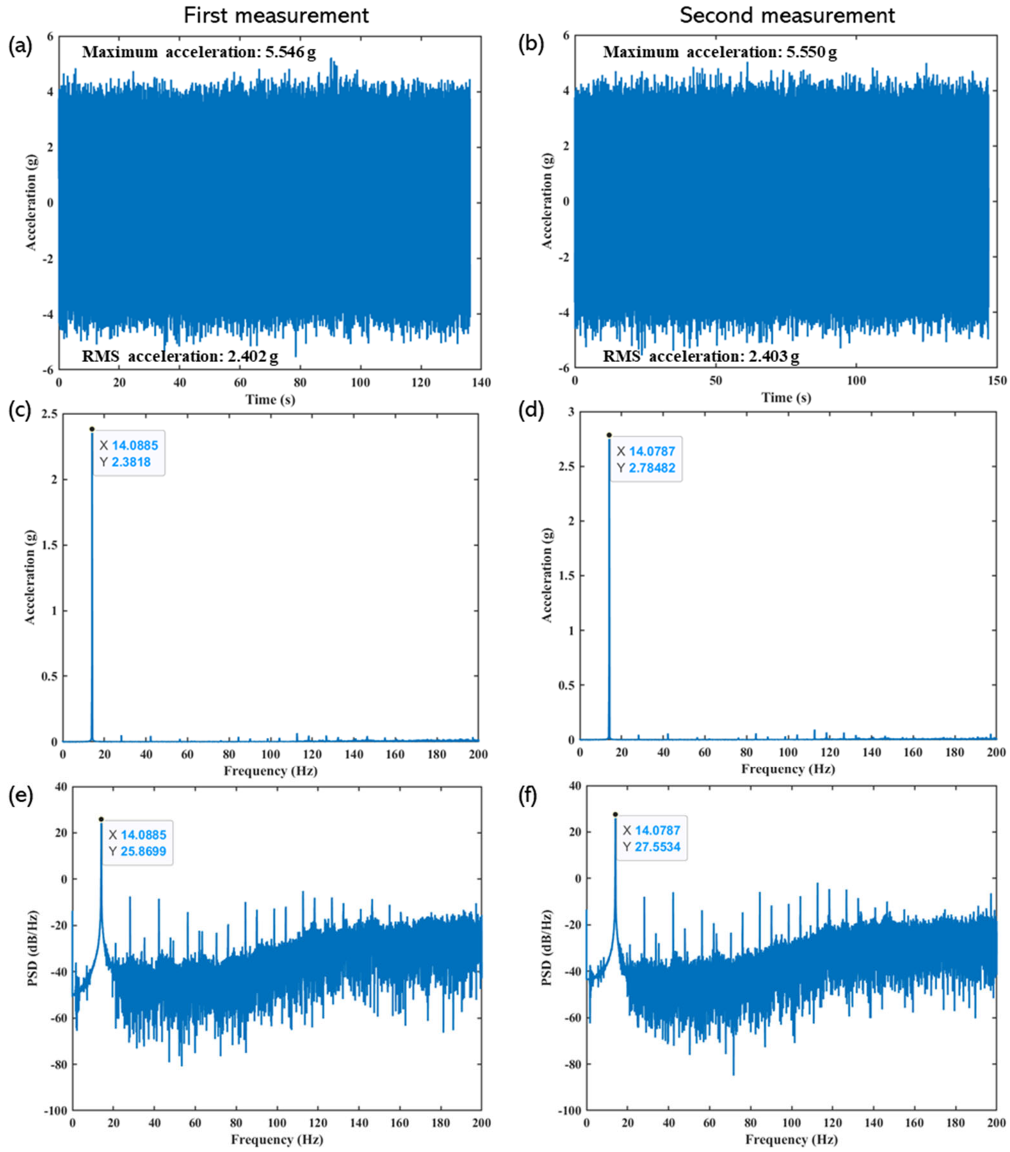


FIG 5 – Short-term vibration data of a fine screen along the y direction: (a) and (b) time history signal of the generated acceleration; (c) and (d) frequency distribution of the generated acceleration; (e) and (f) PSD distribution of the generated acceleration.

TABLE 3

Vibration characteristics of five operating machines and a handrail in a CHPP.

Parameters	x direction (measurements)		y direction (measurements)		z direction (measurements)	
	First	Second	First	Second	First	Second
Fine screen						
RMS acceleration (g)	0.367	0.364	2.402	2.403	2.494	2.491
Maximum acceleration (g)	1.621	1.628	5.546	5.550	4.556	4.567
Dominant frequency (Hz)	14.09	14.08	14.09	14.08	14.09	14.08
Maximum power density (dB/Hz)	-3.75	-2.11	25.87	27.55	26.41	28.08
Centrifuge chute						
RMS acceleration (g)	1.044	1.043	0.096	0.104	0.139	0.140
Maximum acceleration (g)	1.745	1.799	0.408	0.498	0.694	0.703
Dominant frequency (Hz)	24.97	24.97	24.97	24.97	24.97	24.97

Parameters	x direction (measurements)		y direction (measurements)		z direction (measurements)	
	First	Second	First	Second	First	Second
Maximum power density (dB/Hz)	21.03	20.09	-5.04	-5.08	1.96	0.83
Deslime screen						
RMS acceleration (g)	0.139	0.138	1.910	1.912	2.522	2.403
Maximum acceleration (g)	0.638	0.940	3.032	3.025	4.639	4.524
Dominant frequency (Hz)	63.02	63.01	15.75	15.75	15.75	15.75
Maximum power density (dB/Hz)	-3.23	-6.96	26.44	23.00	28.82	25.37
Clean coal screen						
RMS acceleration (g)	0.765	0.724	2.118	2.124	2.634	2.626
Maximum acceleration (g)	4.020	3.437	3.732	3.644	4.324	4.280
Dominant frequency (Hz)	49.48	49.47	16.49	16.49	16.49	16.49
Maximum power density (dB/Hz)	15.22	10.97	25.17	26.74	27.02	28.54
Centrifuge						
RMS acceleration (g)	0.469	0.469	0.466	0.468	0.342	0.346
Maximum acceleration (g)	2.048	2.241	2.522	2.200	1.489	1.548
Dominant frequency (Hz)	24.91	25.00	24.91	24.92	25.00	25.00
Maximum power density (dB/Hz)	4.02	3.97	1.23	-1.03	3.07	4.00
Handrail						
RMS acceleration (g)	0.373	0.362	1.152	1.105	0.103	0.102
Maximum acceleration (g)	1.364	1.156	2.142	2.079	0.334	0.333
Dominant frequency (Hz)	9.82	9.82	24.96	24.96	24.96	24.96
Maximum power density (dB/Hz)	9.61	10.75	19.81	19.34	-3.23	-3.04

The long-term vibration data were collected from a centrifuge chute and a deslime screen. The vibration data obtained from the centrifuge chute had a duration of 9.37 hrs with a sampling frequency of 406 Hz. According to the time history signal of the acceleration produced by a centrifuge chute along the x direction (Figure 6a), the vibration initially remained steady. After approximately 88 mins, the vibration slightly decreased and maintained this level for around 41 mins. Then, the vibration suddenly dropped to nearly zero for about 10 mins. Afterward, despite some fluctuations, the centrifuge chute consistently generated stable vibrations for the remaining hours. However, the Fast Fourier Transform result of the produced vibration (Figure 6b) indicated that the dominant frequency of the centrifuge chute in the x direction was stable, which was 24.88 Hz throughout the entire monitoring period. Similar trends could also be observed in the y and z directions.

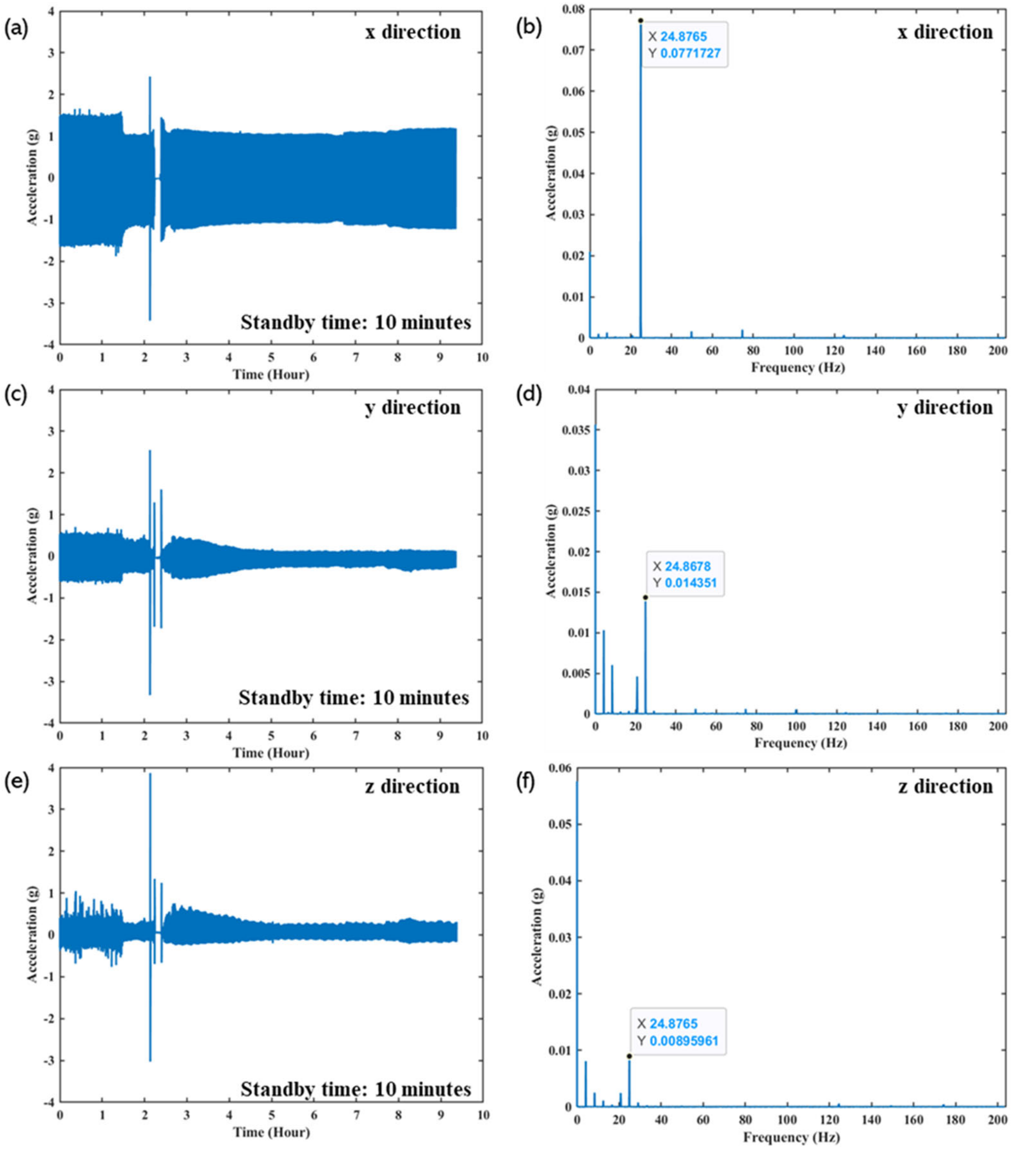


FIG 6 – Long-term vibration data of a centrifuge chute: (a), (c) and (e) time history signal of the generated acceleration along the x, y and z directions; (b), (d) and (f) frequency distribution of the generated acceleration along the x, y and z directions

The vibration generated by the deslime screen was measured continuously for 22.75 hrs with a sampling frequency of 404 Hz. As shown in Figure 7, the vibration produced by the deslime screen suddenly decreased to almost 0 after 140 mins and maintained this state for approximately 4 hrs. Although the dominant frequency of the deslime screen remained consistent throughout the monitoring period, obvious fluctuations in acceleration can be observed in the time history signals along the x and z directions. Overall, the vibration generated by both machines was discontinuous and unstable throughout the monitoring period. According to the shift report from the mine site, this behaviour was attributed to the intermittent operation of the CHPP during that time. Once the CHPP returns to normal working conditions, the operating machines in the plant are expected to continuously generate abundant and stable vibrations, which can be used for vibration energy harvesting.

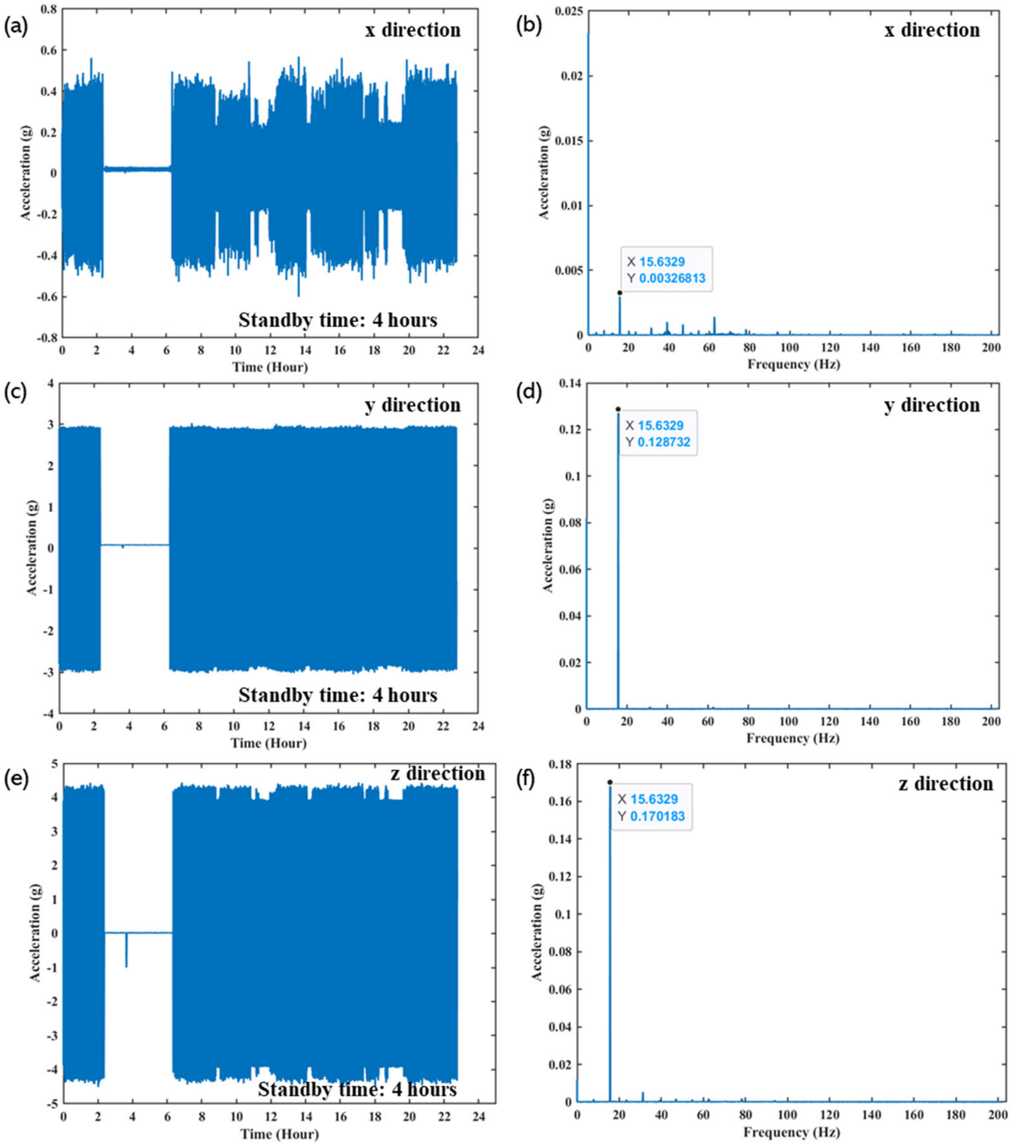


FIG 7 – Long-term vibration data of a deslime screen: (a), (c) and (e) time history signal of the generated acceleration along the x, y and z directions; (b), (d) and (f) frequency distribution of the generated acceleration along the x, y and z directions

CONCLUSIONS

This paper provided a brief introduction and comparison of three vibration energy harvesting technologies based on piezoelectric, electromagnetic and electrostatic mechanisms. To demonstrate the potential of the vibration energy harvesting for self-powered sensors, a commercial electromagnetic energy harvester (ReVibe model D) was chosen and its energy harvesting performance was evaluated based on a lab vibrator (3 g, 50 Hz) and an idling SUV automobile (0.3 g, 25 Hz). Experimental results indicate that a ReVibe energy harvester is capable of harvesting vibration energy from operating machines, which can generate adequate electricity to power a sensor. To harness vibrations in mines as much as possible, vibration analysis was conducted based on short-term and long-term vibration data collected from five operating machines and a handrail in a CHPP. The results show that all the measured vibration sources can generate stable and abundant vibrations under normal operations, which are characterised by large amplitudes (up to 5.55 g) and low dominant frequencies (14 Hz to 25 Hz). Therefore, the operating machines in the CHPP can be considered as potential vibration sources at mine sites for vibration energy harvesting.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge support from the Australian Coal Industry's Research Program (ACARP) project – ACARP Project C33033.

REFERENCES

Aabid, A, Raheman, M A, Ibrahim, Y E, Anjum, A, Hrairi, M, Parveez, B, Parveen, N and Mohammed Zayan, J, 2021. A Systematic Review of Piezoelectric Materials and Energy Harvesters for Industrial Applications, *Sensors*, 21(12):4145. https://doi.org/10.3390/s21124145

Jasiulek, D, Stankiewicz, K and Woszczyński, M, 2016. Intelligent Self-Powered Sensors in the State-of-the-Art Control Systems of Mining Machines, *Archives of Mining Sciences*, 61(4):907–915. https://doi.org/10.1515/amsc-2016-0060

Le, M Q, Capsal, J-F, Lallart, M, Hebrard, Y, Van Der Ham, A, Reffe, N, Geynet, L and Cottinet, P-J, 2015. Review on energy harvesting for structural health monitoring in aeronautical applications, *Progress in Aerospace Sciences*, 79:147–157. https://doi.org/10.1016/j.paerosci.2015.10.001

Liu, H, Zhong, J, Lee, C, Lee, S-W and Lin, L, 2018. A comprehensive review on piezoelectric energy harvesting technology: Materials, mechanisms and applications, *Applied Physics Reviews*, 5(4):041306. https://doi.org/10.1063/1.5074184

Molaei, F, Rahimi, E, Siavoshi, H, Ghaychi Afrouz, S and Tenorio, V, 2020. A Comprehensive Review on Internet of Things (IoT) and its Implications in the Mining Industry, *Am J Eng Appl Sci*, 13:499–515. https://doi.org/10.3844/ajeassp.2020.499.515

Rodriguez, J C, Nico, V and Punch, J, 2019. A Vibration Energy Harvester and Power Management Solution for Battery-Free Operation of Wireless Sensor Nodes, *Sensors*, 19(17):3776. https://doi.org/10.3390/s19173776

Sezer, N and Koç, M, 2021. A comprehensive review on the state-of-the-art of piezoelectric energy harvesting, *Nano Energy*, 80:105567. https://doi.org/10.1016/j.nanoen.2020.105567

Shirvanimoghaddam, M, Shirvanimoghaddam, K, Abolhasani, M M, Farhangi, M, Zahiri Barsari, V and Liu, H, 2019. Towards a Green and Self-Powered Internet of Things Using Piezoelectric Energy Harvesting, *IEEE Access*, 7:94533–94556. https://doi.org/10.1109/ACCESS.2019.2928523

Sisinni, E, Saifullah, A, Han, S, Jennehag, U and Gidlund, M, 2018. Industrial Internet of Things: Challenges, Opportunities and Directions, *IEEE Transactions on Industrial Informatics*, 14(11):4724–4734. https://doi.org/10.1109/TII.2018.2852491

Sundriyal, P and Bhattacharya, S, 2019. Energy Harvesting Techniques for Powering Wireless Sensor Networks in Aircraft Applications: A Review, pp 55–76. https://doi.org/10.1007/978-981-13-3290-6_4

Wei, C and Jing, X, 2017. A comprehensive review on vibration energy harvesting: Modelling and realization, *Renewable and Sustainable Energy Reviews*, 74:1–18. https://doi.org/10.1016/j.rser.2017.01.073

Yun, M and Yuxin, B, 2010. Research on the architecture and key technology of Internet of Things (IoT) applied on smart grid, in *Proceedings of the 2010 International Conference on Advances in Energy Engineering*, pp 69–72. https://doi.org/10.1109/ICAEE.2010.5557611

Zhou, C, Damiano, N and Whisner, B, 2017. Industrial Internet of Things (IIoT) applications in underground coal mines, *Mining Engineering*, 69:50–56. https://doi.org/10.19150/me.7919

Mining in extreme environments and unconventional deposits

Estimating the thickness of the Martian subsurface layer based on the fault pattern

D Asahina[1], B Bradák[2], S Akdag[3] and S Saydam[4]

1. Senior Scientist, Geological Survey of Japan, AIST, Ibaraki, 305–8567, Japan. Email: d-asahina@aist.go.jp
2. Associate Professor, Faculty of Oceanology, Kobe University, Kobe 658–0022, Japan. Email: bradak.b@port.kobe-u.ac.jp
3. Postdoctoral research fellow, School of Minerals and Energy Resources Engineering, UNSW Sydney, Kensington NSW 2052. Email: s.akdag@unsw.edu.au
4. Professor, School of Minerals and Energy Resources Engineering, UNSW Sydney, Kensington NSW 2052. Email: s.saydam@unsw.edu.au

INTRODUCTION

Human exploration of Mars has been on the horizon of scientific goals for decades now, and as part of the objectives of human missions to various planets, one of the possible goals is opening new economic frontiers by the potential extraction and utilisation of resources, eg mining minerals and using surface regolith (Neukart, 2024). A comprehensive understanding of surface morphology, lithostratigraphy, basic structural geology, and civil engineering technology is essential to conduct mining operations for resource extraction on extraterrestrial planets. For instance, proper assessment of the risks associated with excavation and infrastructure construction under unique environments such as low gravity, surface irregularities, and the presence of regolith is fundamental.

Such knowledge has been accumulated through satellite imagery and numerical topographic data using remote sensing technology, as well as seismic surveys by the on-site lander (Knapmeyer-Edrun *et al,* 2021; Banerdt *et al,* 2020; Giardini *et al,* 2020). Recent studies show that Marsquakes could be caused by the release of strain energy generated by the contraction of Mars. In particular, Marsquakes occur around the graben where many faults exist and form regularly spaced patterns. This implies that Marsquakes occur when the stress field of the Martian crust is an extension condition, and normal faults appear on the surface.

In this study, we focus on so-called graben structures, one of Mars's common tectonic structures (Plescia, 1991; Banerdt *et al*, 1992; Hoogenboom Hagen, 2014). The study aims to provide additional information about the tectonic environment during the formation of such features and, in addition, the internal mechanical-rheological structure of Mars, revealed by the geometrical pattern of faults modelled and simulated in a laboratory environment.

Particularly, this research targets the relationship between the fault spacing and the thickness of the mechanical layer as an approach to gain additional information about the internal structure from satellite images. To do so, we focus on the mechanical layer, a stratigraphic unit which is composed of the same mechanical properties and is mainly bounded by lithology. Estimating the mechanical layer is important, considering potential resource exploration on Mars and the prospective construction of civil engineering structures in the future.

POSSIBLE TARGET LOCATIONS ON MARS

As a forming process of graben structures, shallow dyke intrusion and widening have been proposed as a cause of surface faulting and graben formation on Earth by, eg Mastin and Pollard (1988), and the hypothesis has been applied to various (linear and/or radial) graben systems appearing on the surface of Mars (Head and Wilson, 1993; Wilson and Head, 2002). However, some parts of the model of near-surface stresses caused dyke emplacement as the forming process has been challenged over time (Wyrick *et al*, 2015; Hardy, 2016). There are some key locations on Mars where graben (and horst and graben) structures have been under investigation for decades and serve as model areas for such processes on Mars. One of the most often referred locations can be found in the Tharsis region, studied by eg Plescia (1991), Davis, Tanaka and Golombek (1995), Mège and Masson (1996), and Nahm and Schultz (2011), many investigating the graben structures of Thaumasia Fossae (eg 'Fractured highlands' in Pieterek *et al,* 2024) and Ceraunius Fossae

(Borraccini *et al,* 2005). Further studies target other parts of the Southern Hemisphere, including eg the Noachis Terra and the neighbourhood of Noctis Labyrinthus (Bistacchi, Massironi and Baggio, 2004) (Figure 1).

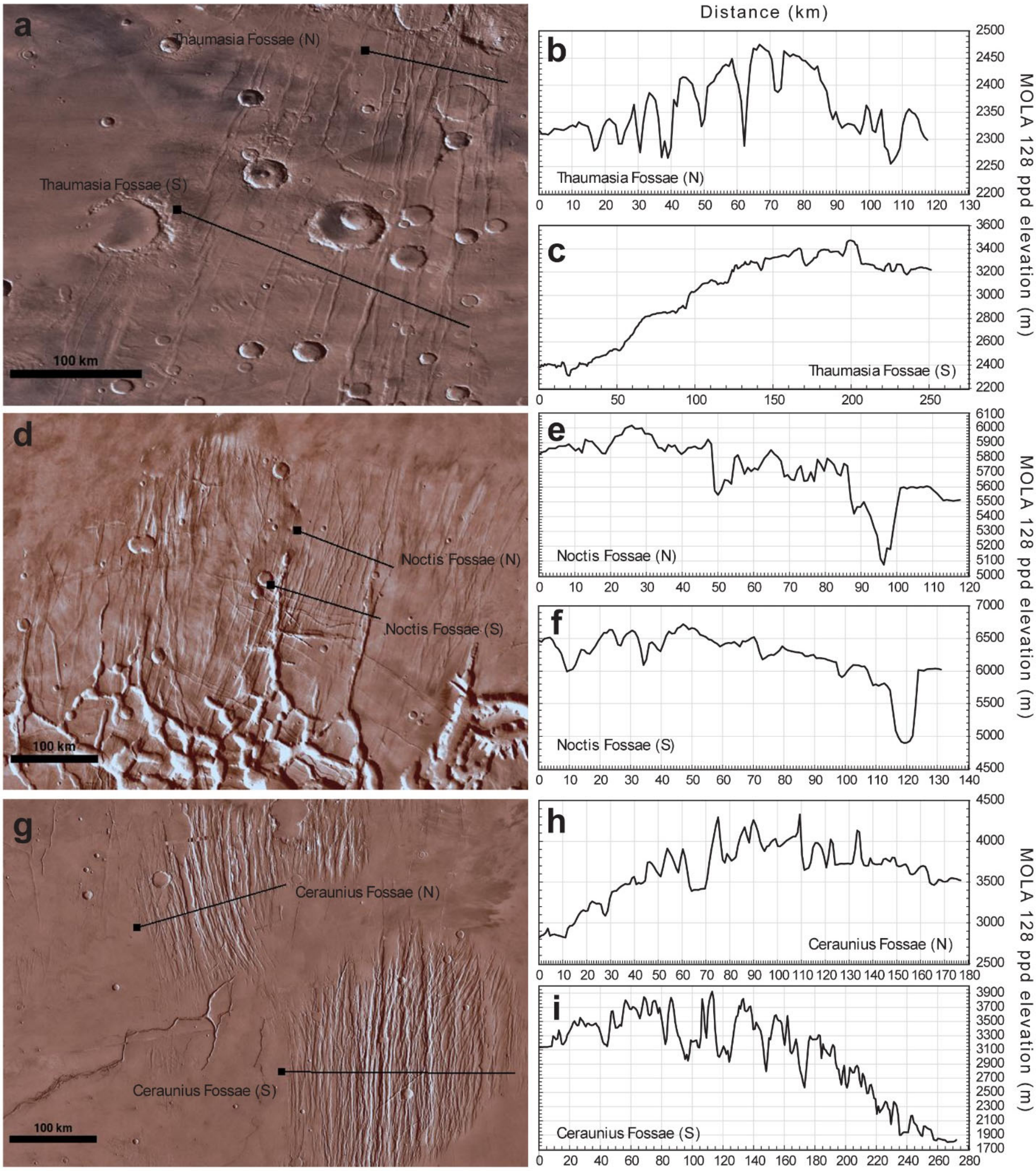


FIG 1 – Examples of characteristic graben (fossae) structures from Mars and their topographic cross-section, such as Thaumasia Fossae (a-c), Noctis Fossae (d-f), and Ceraunius Fossae (g-i) (JMars GIS software images and analysis). The solid black lines on the satellite images indicates the locations of the topographic sections. The small square at one of the ends of the solid black lines marks the 0 km (starting point) of the topographic cross-sections.

Regarding the formation of various tectonic structures seismic activity, one of the key candidate processes is believed to originate from plate movements caused by the contraction-induced deformation. Surface rupture observed along eg rift zones suggests that the Martian crust undergoes an extensional stress field, resulting in faults visibly appearing on the Mars surface (Figure 1).

MODEL EXPERIMENTS

Here, we focus on the relationship between the fault spacing and the thickness of the mechanical layer, with the aim of obtaining more information from satellite images, particularly regarding the internal structure. The so-called 'mechanical layer' comprises the same mechanical properties and is mainly delimited by lithological variations (Narr, 1991; Gross, 1993). Empirical relationships of the mechanical layer thickness-fault spacing reveal a linear relationship (Narr and Suppe, 1991). Maerten, Gillespie and Pollard (2002) demonstrated the impact of stress drop zones (stress shadows) generated by faulting activities on fault spacing. Figure 2 show an example of the application of fault spacing on Mars based on these fault spacings determined on Earth and the thickness of the mechanical layer.

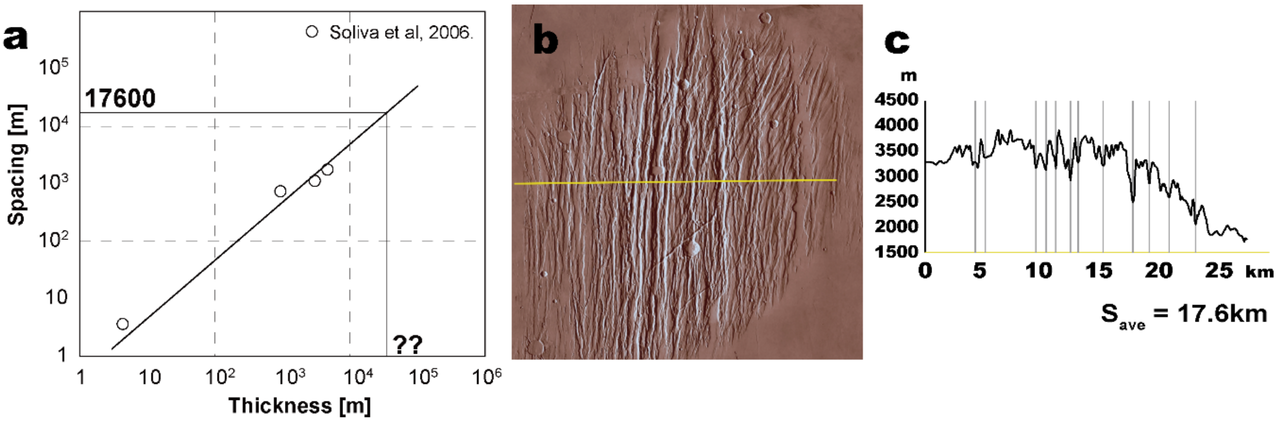


FIG 2 – Estimation of the mechanical layer thickness of Mars based on the fault spacing: (a) relationship between fault spacing and mechanical layer thickness (Soliva, Benedicto and Maerten, 2006), (b) illustration of faults in the Ceraunius Fossae region with a highlighted yellow scan line (source: Mars Trek), (c) elevation differences along the scan line in (b) (Tsukurimichi *et al,* 2022).

The thickness of the mechanical layer, as shown here, can be verified on Earth through borehole drilling or seismic surveys. Maeda *et al* (2019) conducted a survey of the normal fault in Miyako-jima Island, Japan, discussing the consistency between the mechanical layer thickness and other geological features such as seismic activities, P-wave velocities, and borehole data. However, in cases like Mars, where detailed studies are impractical, one approach to validate the mechanical layer thickness involves comparing it with the thickness distribution of the Martian crust, estimated from Bouguer gravity (Genova *et al*, 2016). However, while the Martian crust's thickness derived from Bouguer gravity exhibits regional variations, its consistency with the mechanical layer has not been examined so far. It's imperative to conduct fault spacing and mechanical layer thickness calculations across various locations to discern prevailing trends through comparative analyses.

The identification of faults in remote areas also poses challenges when relying on surface-based two-dimensional observation. Various method for extracting normal faults in remote environments such as Mars have been studied. Hauber and Kronberg (2001) assumed a cross-sectional configuration of the fault structure of Tempe fossa. Borraccini *et al* (2005) measured the fault displacement and assessed the extent of tensile deformation. Such refined fault detection methods not only enhance fault identification but also prove beneficial for estimating mechanical layer thickness.

CONCLUSION

The method proposed here is to use satellite imagery to estimate the thickness of mechanical layer in remote locations such as Mars. Knowing such thickness may support Martian mining operations during many phases of the mining process including:

- Exploration, when it may be the key to know the thickness of resource covering material.
- Development, when determination of various layers (eg the uppermost less compacted regolith) may be the part of hazard mitigation.

- Production, when estimating the thickness of the stratigraphic unit, containing the resource feels essential.

In light of these examples, knowing the subsurface geological structure in advance could play an important role in supporting future drilling activities on the Red Planet and facilitating the utilisation of extraterrestrial resources.

REFERENCES

Banerdt, W B, Golombek, M P and Tanaka, K L, 1992. Stress and tectonics on Mars, in *Mars* (ed: H H Kieffer), pp 249–297 (University of Arizona Press: Tucson).

Banerdt, W B, Smrekar, S E, Banfield, D, Giardini, D, Golombek, M, Johnson, C L, Lognonné, P, Spiga, A, Spohn, T, Perrin, C, Stähler, S C, Antonangeli, D, Asmar, S, Beghein, C, Bowles, N, Bozdag, E, Chi, P, Christensen, U, Clinton, J, Collins, G S, Daubar, I, Dehant, V, Drilleau, M, Fillingim, M, Folkner, W, Garcia, R F, Garvin, J, Grant, J, Grott, M, Grygorczuk, J, Hudson, T, Irving, J C E, Kargl, G, Kawamura, T, Kedar, S, King, S, Knapmeyer-Endrun, B, Knapmeyer, M, Lemmon, M, Lorenz, R, Maki, J N, Margerin, L, McLennan, S M, Michaut, C, Mimoun, D, Mittelholz, A, Mocquet, A, Morgan, P, Mueller, N T, Murdoch, N, Nagihara, S, Newman, C, Nimmo, F, Panning, M, Pike, W T, Plesa, A-C, Rodriguez, S, Rodriguez-Manfredi, J A, Russell, C T, Schmerr, N, Siegler, M, Stanley, S, Stutzmann, E, Teanby, N, Tromp, J, Driel, M V, Warner, N, Weber, R and Wieczorek, M, 2020. Initial results from the InSight mission on Mars, *Nat Geosci,* 13:183–189. https://doi.org/10.1038/s41561-020-0544-y

Bistacchi, N, Massironi, M and Baggio, P, 2004. Large-scale fault kinematic analysis in Noctis Labyrinthus (Mars), *Planetary and Space Science*, 52(1–3):215–222. https://doi.org/10.1016/j.pss.2003.08.015

Borraccini, F, Lanci, L, Wezel, F C and Baioni, D, 2005. Crustal extension in the Ceraunius Fossae, northern Tharsis region, Mars, *Journal of Geophysical Research: Planets*, 110(E6). https://doi.org/10.1029/2004JE002373

Davis, P A, Tanaka, K L and Golombek, M P, 1995. Topography of closed depressions, scarps and grabens in the north Tharsis region of Mars: Implications for shallow crustal discontinuities and graben formation, *Icarus*, 114(2):403–422. https://doi.org/10.1006/icar.1995.1071

Genova, A, Goossens, S, Lemoine, F G, Mazarico, E, Neumann, G A, Smith, D E and Zuber, M T, 2016. Seasonal and static gravity field of Mars from MGS, Mars Odyssey and MRO radio science, *Icarus,* 272:228–245. http://dx.doi.org/10.1016/j.icarus.2016.02.050

Giardini, D, Lognonné, P, Banerdt, W B, Pike, W T, Christensen, U, Ceylan, S, Clinton, J F, van Driel, M, Stähler, S C, Böse, M, Garcia, R F, Khan, A, Panning, M, Perrin, C, Banfield, D, Beucler, E, Charalambous, C, Euchner, F, Horleston, A, Jacob, A, Kawamura, T, Kedar, S, Mainsant, G, Scholz, J-R, Smrekar, S E, Spiga, A, Agard, C, Antonangeli, D, Barkaoui, S, Barrett, E, Combes, P, Conejero, V, Daubar, I, Drilleau, M, Ferrier, C, Gabsi, T, Gudkova, T, Hurst, K, Karakostas, F, King, S, Knapmeyer, M, Knapmeyer-Endrun, B, Llorca-Cejudo, R, Lucas, A, Luno, L, Margerin, L, McClean, J B, Mimoun, D, Murdoch, N, Nimmo, F, Nonon, M, Pardo, C, Rivoldini, A, Rodriguez Manfredi, J A, Samuel, H, Schimmel, M, Stott, A, Stutzmann, E, Teanby, N, Warren, T, Weber, R C, Wieczorek, M and Yana, C, 2020. The seismicity of Mars, *Nat Geosci,* 13:205–212. https://doi.org/10.1038/s41561-020-0539-8

Gross, M R, 1993. The origin and spacing of cross joints: examples from the Monterey Formation, Santa Barbara Coastline, California, *J Structural Geology*, 15(6):737–751. https://doi.org/10.1016/0191-8141(93)90059-J

Hardy, S, 2016. Does shallow dike intrusion and widening remain a possible mechanism for graben formation on Mars?, *Geology*, 44(2):107–110. https://doi.org/10.1130/G37285.1

Hauber, E and Kronberg, P, 2001. TempeFossae, Mars' A planetary analogon to a terrestrial continental rift?*, Journal of Geophysical Research*, 106(E9):20587–20602.

Head, J W and Wilson, L, 1993. Lunar graben formation due to near-surface deformation accompanying dike emplacement, *Planet Space Sci,* 41:719–727 https://doi.org/10.1016/0032-0633(93)90114-H

Hoogenboom Hagen, T, 2014. Graben, in *Encyclopedia of Planetary Landforms* (Springer: New York), https://doi.org/10.1007/978-1-4614-9213-9_177-1

Knapmeyer-Endrun, B, Panning, M P, Bissig, F, Joshi, R, Khan, A, Kim, D, Lekić, V, Tauzin, B, Tharimena, S, Plasman, M, Compaire, N, Garcia, R F, Margerin, L, Schimmel, M, Stutzmann, E, Schmerr, N, Bozdağ, E, Plesa, A-C, Wieczorek, M A, Broquet, A, Antonangeli, D, McLennan, S M, Samuel, H, Michaut, C, Pan, L, Smrekar, S E, Johnson, C L, Brinkman, N, Mittelholz, A, Rivoldini, A, Davis, P M, Lognonné, P, Pinot, B, Scholz, J-R, Stähler, S, Knapmeyer, M, van Driel, M, Giardini, D and Banerdt, W B, 2021. Thickness and structure of the Martian crust from InSight seismic data, *Science,* 373(6553):438–44. https://doi.org/10.1126/science.abf8966

Maeda, S, Otsubo, M, Asahina, D and Furuno, Y, 2019. Estimating the thickness of a faulted mechanical layer based on fault spacing: An example from Miyako-jima Island, southern Ryukyu Arc, Japan, *Island Arc*, e12336. https://doi.org/10.1111/iar.12336

Maerten, L, Gillespie, P and Pollard, D D, 2002. Effects of local stress perturbation on secondary fault development, *Journal of Structural Geology,* 24:145–153.

Mastin, L G and Pollard, D D, 1988. Surface deformation and shallow dike intrusion processes at Inyo craters, Long Valley, California: *Journal of Geophysical Research*, 93:13221–13235. https://doi.org/10.1029/JB093iB11p13221

Mège, D and Masson, P, 1996. Stress models for Tharsis formation, Mars, *Planetary and Space Science*, 44(12):1471–1497. https://doi.org/10.1016/S0032-0633(96)00112-2

Nahm, A L and Schultz, R A, 2011. Magnitude of global contraction on Mars from analysis of surface faults: Implications for Martian thermal history, *Icarus*, 211(1):389–400. https://doi.org/10.1016/j.icarus.2010.11.003

Narr, W and Suppe, J, 1991. Joint spacing in sedimentary rocks, *Journal of Structural Geology*, 13(9):1037–1048. https://doi.org/10.1016/0191-8141(91)90055-N

Narr, W, 1991. Fracture density in the deep subsurface: techniques with application to Point Arguello oil field, *American Association of Petroleum Geologists Bulletin*, 75(8):1300–1323. https://doi.org/10.1306/0c9b2939-1710-11d7-8645000102c1865d

Neukart, F, 2024. Towards sustainable horizons: A comprehensive blueprint for Mars colonization, *Heliyon,* https://doi.org/10.1016/j.heliyon.2024.e26180

Pieterek, B, Brož, P, Hauber, E and Stephan, K, 2024. Insight from the Noachian-aged fractured crust to the volcanic evolution of Mars: A case study from the Thaumasia graben and Claritas Fossae, *Icarus*, 407:115770. https://doi.org/10.1016/j.icarus.2023.115770

Plescia, J B, 1991. Graben and extension in northern Tharsis, Mars, *Journal of Geophysical Research*: *Planets*, 96(E3):18883–18895. https://doi.org/10.1029/91JE02005

Soliva, R, Benedicto, A and Maerten, L, 2006. Spacing and linkage of confined normal faults: Importance of mechanical thickness, *Journal of Geophysical Research*: *Solid Earth*, 111(1):1–17. https://doi.org/10.1029/2004JB003507

Tsukurimichi, Y, Takemura, T, Asahina, D and Endo, T, 2022. Investigation of the internal mechanical structure of Mars based on geometrical patterns of faults, in Proceedings of the Australasian Ground Control Conference – An ISRM Regional Symposium (AUSROCK) (The Australasian Institute of Mining and Metallurgy: Melbourne).

Wilson, L and Head, J W, 2002. Tharsis-radial graben systems as the surface manifestation of plume related dike intrusion complexes: models and implications, *J Geophys Res,* 107. https://doi.org/10.1029/2001JE001593

Wyrick, D Y, Morris, A P, Todt, M K and Watson-Morris, M J, 2015. Physical analogue modelling of Martian dyke-induced deformation, in (eds: T Platz, P K Byrne, M Massironi and H Hiesinger), *Volcanism and Tectonism Across the Inner Solar System*: *Geological Society of London Special Publication,* 401:395–403. https://doi.org/10.1144/sp401.15

Cabeus Crater lunar volatiles and their effect on human exposure limitations

N Barnett[1], J Oh[2], A G Dempster[3] and S Saydam[4]

1. PhD Candidate, School of Minerals and Energy Resources Engineering, UNSW Sydney, Sydney NSW 2052. Email: nicholas.barnett@student.unsw.edu.au
2. Associate Professor, School of Minerals and Energy Resources Engineering, UNSW Sydney, Sydney NSW 2052. Email: joung.oh@unsw.edu.au
3. Professor, School of Electrical Engineering and Telecommunications; Director, Australian Centre for Space Engineering Research, UNSW Sydney, Sydney NSW 2052. Email: a.dempster@unsw.edu.au
4. Professor, School of Minerals and Energy Resources Engineering; Deputy Director, Australian Centre for Space Engineering Research, UNSW Sydney, Sydney NSW 2052. Email: s.saydam@unsw.edu.au

ABSTRACT

NASA's Artemis III mission is expected to return astronauts to the surface to explore and sample the lunar volatiles by 2026. These volatiles are anticipated to provide scientific insights as to how the Moon was created and economic value to off-Earth operations. These same volatiles can pose health implications to astronauts and Earth based personnel handling lunar regolith samples. Using Australian, USA and NASA airborne contaminant exposure limits and the Lunar CRater Observation and Sensing Satellite (LCROSS) measurements of lunar volatiles in the Cabeus crater ejecta, the minimum mass of lunar regolith that can be safely handled by humans on Earth and in spacecraft can be calculated. This analysis determined a 0.15 grams pure sample of Cabeus crater regolith within a cubic metre of air has enough volatiles to exceed safe working conditions, and 14.9 grams of pure Cabeus crater regolith per cubic metre of air can impact human life.

The intent of this analysis is to assist safe handling and exposure calculations for the safe handling procedures of lunar regolith containing volatiles.

INTRODUCTION

After the Apollo missions, the Moon was considered devoid of volatiles with the exception of the lunar poles, where permanent shadowing of the crater rims sustained cryogenic temperatures in which volatiles could exist in a solid phase (Hurley *et al*, 2023). In 2009, a spent Centaur upper stage was crashed into a permanently shadowed region of the Cabeus crater, with the Lunar CRater Observation and Sensing Satellite (LCROSS) onboard the Lunar Reconnaissance Orbiter (LRO) to observe the resulting ejecta plume for signs of volatiles (Gladstone *et al*, 2010). Measurements by LCROSS of the Cabeus crater ejecta plume indicated the presence of water, hydrogen sulfide, ammonia, sulfur dioxide, ethylene, carbon dioxide, methanol, methane and hydroxide (Table 1) (Colaprete *et al*, 2010; Luchsinger, Chanover and Strycker, 2021).

TABLE 1

Abundance of volatiles in the Cabeus crater ejecta plume and the relative concentration of volatiles within the lunar regolith at the point of impact (Colaprete *et al*, 2010).

Compound	% Relative to H2O (g)	Relative to lunar regolith (wt%)
H_2O	100.00%	5.6
H_2S	16.75%	0.938
NH_3	6.03%	0.338
SO_2	3.19%	0.179
C_2H_4	3.12%	0.175
CO_2	2.17%	0.122
CH_3OH	1.55%	0.0868
CH_4	0.65%	0.0364
OH	0.03%	0.00168

In 2024, the National Aeronautics and Space Administration (NASA) announced the Artemis III mission will return humans to the Moon in 2026, landing in the lunar south pole (Donaldson, 2024). One of the seven overarching science objectives of the mission is to understand the origin and character of the lunar polar volatiles, with humans performing *in situ* measurements and returning samples of lunar volatiles for further analysis on Earth (NASA, 2020). Human exposure to these contaminants via scientific examination of samples, habitats made from lunar regolith, oxygen recovery methods from lunar regolith, tracking trace samples into habitats on equipment and/or space suits, or other exposure points, could impact human health.

Volatiles are substances that in normal Earth temperature conditions can exist either in a gaseous phase, undergo a phase change between gaseous and liquid, or from solids to gas (Vo and Morris, 2014). Elevated levels of volatiles in the atmosphere, or airborne contaminants, can impact human health. To safeguard humans from airborne contaminants, safe working exposure standards outlined by government and scientific bodies, including Australia's Safe Work Australia (SWA), the American Conference of Governmental Industrial Hygienists (ACGIH), and the National Institute of Occupational Safety and Health (NIOSH), as the maximum exposure limits for each volatile (Table 2). Exposure standards for airborne contaminants include time weighted average (TWA), short-term exposure limits (STEL) and/or peak limitation, where exposure is not to exceed any of the outlined standards (Talty, 1998) (Table 3).

TABLE 2

Safe work exposure limits in parts per million (ppm) outlined by SWA, ACGIH and NIOSH.

Volatile	SWA		ACGIH		NIOSH		
	TWA (ppm)	STEL (ppm)	TWA (ppm)	STEL (ppm)	TWA (ppm)	STEL (ppm)	IDLH (ppm)
H_2S	10	15	1	5	NA	$10^{\pm}$	100
NH_3	20	35	25	35	25	35	300
SO_2	NA	0.25	NA	0.25	2	5	100
CH_3OH	200	250	200	250	200	250	6000

NA: No data available or produced for this exposure limit. NA*: Insufficient data to perform risk-based assessment. ± NIOSH STEL maximum exposure limit is 10 mins.

TABLE 3

Descriptions of safe work limits by Agency/Scientific body.

Agency/ Scientific body	Abbreviation	Description
SWA	TWA	Time weighted average exposure threshold over a 8 hr work day for a 40 hr work week.
	STEL	Short-term exposure limit for a maximum period of 15 mins.
ACGIH	TLV-TWA	Threshold limit value (TLV) time weighted average over a 8 hr work day for a 40 hr work week.
	TLV-STEL	Short-term exposure limit for a maximum period of 15 mins.
NIOSH	TWA	Recommended airborne exposure limit (REL) for a time weighted average over a 10 hr work day for a 40 hr work week.
	ST	Short-term exposure limit for a maximum period of 15 mins.
	IDLH	Immediate dangerous to life or health exposure limit.

For spacecraft or off-Earth environments outlined in NASA's Spaceflight Human-system Standard Volume 2: Human Factors, Habitability, and Environmental Health (NASA-STD-3001) (NASA, 2023)), NASA's Spacecraft Maximum Allowable Concentrations for Airborne Contaminants (JSC 20584) provides the maximum exposure limits (NASA, 2022), where humans could have long-term exposure to the volatiles without a reprieve to expel toxins (Table 4). Exposure standards provide continuous short-term (1 to 24 hr) exposure limits for accidental spills and nominal limits for seven through to 1000 days of continuous exposure (NASA, 2022).

TABLE 4

Long-term continuous safe exposure limits in parts per million (ppm) outlined by NASA (NASA, 2022).

Volatile	1 hr (ppm)	24 hrs (ppm)	7 days (ppm)	30 days (ppm)	180 days (ppm)	1000 days (ppm)
H_2S	5	1.3	1.3	1.3	0.3	NA*
NH_3	30	20	3	3	3	3
SO_2	NA	NA	NA	NA	NA	NA
CH_3OH	70	70	20	20	20	10

NA: No data available or produced for this exposure limit. NA*: Insufficient data to perform risk-based assessment.

Asphyxiants, non-toxic volatiles that lead to a reduction in the breathable oxygen within the environment via dissolution or displacement, and volatiles that are explosive or flammable within an environment, can result in harm to human health. For asphyxiants, the minimum oxygen level in an environment is 19.5 per cent by volume. In explosive atmospheres, the Lower Explosive Limit (LEL), or minimum concentration of the volatile in the environment that can result in combustion, defines the safe human exposure limits.

Using the maximum safe work and continuous long-term exposure limits, this paper examines the methodology to determine the exposure of time weighted average for lunar airborne contaminants for humans in spacecraft and on Earth.

METHODOLOGY

As the nature and sublimation rate of volatiles within a sample of regolith is not known, and varying influences will affect the exposure of humans to the lunar volatiles, this study made the following assumptions:

- The lunar regolith sample will contain the species and concentration of volatiles as detected in the Cabeus crater ejecta (Table 1) (Colaprete *et al*, 2010).
- No volatiles will be lost in the regolith sample during extraction and transportation to the spacecraft habitat or Earth-based workspace.
- Atmospheric environments for Earth-based and spacecraft will be 25°C and 1 atmosphere pressure (101.3 kPa or 760 torr).
- Inspired partial pressure of oxygen will be 2.9 psia.
- Atmosphere will be filled with dry air.
- Exposure point will not have any filtration system to remove air borne contaminants from the atmosphere.
- The entire mass of the volatiles within the lunar regolith sample sublimate out when exposed to 25°C and 1 atmosphere pressure conditions, with the entire volatile mass transitioning from solid to gaseous phase in the atmosphere.
- The volatiles will distribute evenly throughout the atmosphere – no accumulation or pockets of airborne toxins in the atmosphere.
- Only one volatile acting as a contaminant is present in the atmosphere at any one time.

For this methodology, the exposure limits for each volatile within the atmosphere were calculated as grams per cubic metre, and mass of the maximum allowable regolith to be within the atmosphere in grams per cubic metre.

Mass of airborne volatiles

With the volatile concentrations in ppm, the mass of individual volatiles in milligrams per cubic metre is to be calculated (Equation 1) (Finucane, 2006).

$$mg/m^3 = ppm\frac{(MW_i)P}{RT} \tag{1}$$

where:

MW_i – Molecular weight of individual volatiles (g/mol)

P – Ambient pressure (psia)

T – Ambient temperature (K)

R – Universal Gas Constant (1.2069 $L.psi.K^{-1}.mol^{-1}$)

Maximum allowable mass of regolith

Using the weight percent formula (Equation 2), the mass of regolith containing the volatiles can be calculated using the volatile concentration values from Table 1.

$$Weight\ percent = \frac{Mass_i}{Mass_{Regolith}} \tag{2}$$

Where:

$Mass_i$ – Mass of the individual volatiles (g)

$Mass_{Total}$ – Mass of the regolith (g)

Weight% – Abundance of the volatile within the lunar regolith (wt per cent)

RESULTS

Using the safe work conditions and continuous spacecraft exposure limits as the maximum concentration of volatiles that can be within an atmosphere, the maximum allowable mass of lunar regolith containing volatiles with concentrations the same as those detected in the Cabeus crater ejecta that can be brought into an atmosphere was calculated (Tables 5 and 6). The calculations assumed the entire mass of the volatiles sublimated and dispersed evenly throughout the atmosphere at the time of exposure.

TABLE 5

Maximum mass of regolith in grams (g) containing concentrations of volatiles similar to the Cabeus crater ejecta that can safely be handled in 1 m^3 volume before exceeding maximum safe work exposure limits. Atmospheric conditions as per Table 1 assuming 25°C and 1 atmosphere pressure and a single volatile is exposed to the atmosphere at a time.

Volatile	SWA		ACGIH		NIOSH		
	TWA (g/m^3)	STEL (g/m^3)	TWA (g/m^3)	STEL (g/m^3)	TWA (g/m^3)	STEL (g/m^3)	IDLH (g/m^3)
H_2S	1.5	2.2	0.15	0.74	NA	1.5	14.9
NH_3	4.1	7.2	5.2	7.2	5.2	7.2	61.8
SO_2	NA	0.37	NA	0.37	2.9	7.3	146.6
CH_3OH	301.7	377.2	301.7	377.2	301.7	377.2	9052.2

NA: No data available or produced for this exposure limit. NA*: Insufficient data to perform risk-based assessment. ± NIOSH STEL maximum exposure limit is 10 mins.

TABLE 6

Maximum mass of regolith in grams (g) containing concentrations of volatiles similar to the Cabeus crater ejecta that can safely be handled in 1 m^3 volume before exceeding maximum long-term continuous exposure limits. Atmospheric conditions as per NASA-STD-3001 assuming 25°C and 1 atmosphere pressure, inspired partial pressure of oxygen at 2.90 psia and a single volatile is exposed to the atmosphere at a time.

Volatile	1 hr (g/m^3)	24 hrs (g/m^3)	7 days (g/m^3)	30 days (g/m^3)	180 days (g/m^3)	1000 days (g/m^3)
H_2S	0.74	0.19	0.19	0.19	0.04	NA*
NH_3	6.2	4.1	0.62	0.62	0.62	0.62
SO_2	NA	NA	NA	NA	NA	NA
CH_3OH	105.6	105.6	30.2	30.2	30.2	15.1

NA: No data available or produced for this exposure limit. NA*: Insufficient data to perform risk-based assessment.

The results found in the concentrations found in lunar samples from the Cabeus crater, low masses of lunar regolith containing hydrogen sulfide, sulfur dioxide and ammonia will exceed safe work exposure limits and continuous spacecraft exposure limits for airborne contaminants. Hydrogen sulfide was found to be the volatile that exceeded the safe work, continuous spacecraft exposure, and immediate dangerous to life or health exposure limits. For safe work exposure limits, 0.15 grams of lunar regolith will reach the maximum exposure limits, with 0.74 grams in reaching the maximum limit for continuous spacecraft exposure, and 14.9 grams before loss of life may occur.

The mass of lunar regolith containing ammonia and sulfur dioxide that would exceed safe work exposure limits was 5.2 grams and 0.37 grams respectively. For spacecraft continuous exposure, a maximum mass of 6.2 grams of lunar regolith containing ammonia for a 1 hr exposure, was sufficient to reach maximum exposure limits. With no available data on the sulfur dioxides impact to human life in continuous spacecraft exposure, the maximum mass of lunar regolith containing sulfur dioxide could not be calculated.

Of the four volatiles used in this study, methanol was found to be the least harmful with 301.7 grams of lunar volatiles containing methanol would reach safe work conditions, 105.6 grams of lunar regolith for continuous spacecraft exposure limits, and 9 kg of lunar regolith containing methanol could result in loss of human life.

DISCUSSION

The study performs a quick look at the minimum mass of lunar regolith containing volatiles that can impact human health. The assumptions used in the study may not represent real world applications as varying factors will influence the mass of volatiles that will dissipate from a sample of lunar regolith, how each volatile exists within the regolith, and the rate the volatiles will sublimate and move around the atmosphere. Without further information as how these influences will affect the toxicity of each volatile, the assumptions used in this study can be used as a 'worst case' scenario for the atmospheric conditions outlined.

The study was not able to calculate the maximum allowable mass of lunar regolith containing lunar volatiles for the varying spacecraft habitable atmospheric pressures and temperatures. NASA's SMACs for airborne contaminants are provided for spacecraft atmospheres that are 25°C and 1 atmosphere pressure (101.3 kPa or 760 torr). As per NASA-STD-3001, spacecraft habitat pressure and temperatures can be between 8.2 psia to 14.7 psia and 18°C to 27°C (NASA, 2023). The impact of varying atmospheric pressures and temperatures will affect human health requires further research.

CONCLUSION

With the return of humans to the Moon to determine the character and origin of lunar volatiles, this study provides a first look at the mass of lunar regolith containing lunar volatiles that can impact human health, and provides methodology to determine the maximum allowable mass of lunar regolith that can safely be introduced to an atmosphere on Earth and in spacecraft. The results from the study indicate the need to perform further research on the impact of lunar volatiles on human health.

REFERENCES

Colaprete, A, Schultz, P, Heldmann, J, Wooden, D, Shirley, M, Ennico, K, Hermalyn, B, Marshall, W, Ricco, A, Elphic, R C, Goldstein, D, Summy, D, Bart, G D, Asphaug, E, Korycansky, D, Landis, D and Sollitt, L, 2010. Detection of water in the LCROSS ejecta plume, *Science*, 330(6003):463–468.

Donaldson, A A, 2024. NASA Shares Progress Toward Early Artemis Moon Missions with Crew, NASA. Available from: <https://www.nasa.gov/news-release/nasa-shares-progress-toward-early-artemis-moon-missions-with-crew/#:~:text=NASA%20will%20now%20target%20September,remains%20on%20track%20for%202028>

Finucane, E W, 2006. *Definitions, Conversions and Calculations for Occupational Safety and Health Professionals,* third edition (CRC Press).

Gladstone, G R, Hurley, D M, Retherford, K D, Feldman, P D, Pryor, W R, Chaufray, J Y, Versteeg, M, Greathouse, T K, Steffl, A J, Throop, H, Parker, J W, Kaufmann, D E, Egan, A F, Davis, M W, Slater, D C, Mukherjee, J, Miles, P F, Hendrix, A R, Colaprete, A and Stern, S A, 2010. LRO-LAMP observations of the LCROSS impact plume, Science, 330(6003):472–476.

Hurley, D M, Siegler, M A, Cahill, J T S, Colaprete, A, Costello, E, Deutsch, A N, Elphic, R C, Fa, W, Grava, C, Hayne, P O, Heldmann, J, Hendrix, A R, Jordan, A P, Killen, R M, Klima, R L, Kramer, G, Li, S, Liu, Y, Lucey, P G, Mazarico, E, Pendleton, Y, Poston, M, Prem, P, Retherford, K D and Schaible, M, 2023. Surface Volatiles on the Moon, *Reviews in Mineralogy and Geochemistry*, 89:787–827.

Luchsinger, K M, Chanover, N J and Strycker, P D, 2021. Water within a permanently shadowed lunar crater: Further LCROSS modeling and analysis, *Icarus*, 354.

NASA, 2020. Artemis III Science Definition Team Report.

NASA, 2022. Spacecraft Maximum Allowable Concentrations for Airborne Contaminants, JSC, 20584. Human Health and Performance Directorate.

NASA, 2023. NASA Spaceflight Human-System Standard, Volume 2: human factors, Habitability and Environmental Health, NASA-STD-3001, Volume 2, Revision, D, NASA.

Talty, J T, 1998. *Industrial Hygiene Engineering,* second edition, Recognition, Measurement, Evaluation and Control (ScienceDirect).

Vo, U T and Morris, M P, 2014. Nonvolatile, semivolatile, or volatile: Redefining volatile for volatile organic compounds, *Journal of the Air and Waste Management Association,* 64(6).

The challenges of producing high purity quartz

D Connelly[1]

1. Principal Consulting Engineer, METS Engineering Group, West Perth WA 6872.
   Email: damian.connelly@metsengineering.com

ABSTRACT

Quartz deposits are common in nature but the presence of quartz suitable for yielding high purity quartz is exceedingly rare. This paper describes a test work study on producing high purity quartz (HPQ) product to meet the tight product specifications of greater than 99.97per cent, including four and even five nines, for uses including, lighting and fibre optics and modern-day high efficiency solar panels. Due to demand in renewable energy applications the market for high purity silica solar panels known for their increasing efficiency and durability is rapidly growing.

Demand continues to rise for the use of high purity quartz in semiconductors, electronics, imaging and sensor markets. Microelectronic components are created by chemically fabricating wafers of semiconductors such as silicon to obtain the desired transport of electrical charge and control of the current. The production of silicon metal from high purity quartz has been designated a Strategic Mineral by the European Commission and by the US Department of Justice due to the growing significance of this metal in various industries. The subsequent processing of quartz is the key step to adding value and aiding technological advances. Overall, the high purity quartz market is a highly secretive, specialised market with increasing opportunities for stakeholders.

The attempt to produce HPQ in this work was carried out using an Australian quartz ore following a typical HPQ process flow sheet. The unit processes included primary crushing, scrubbing, magnetic separation, flotation, acid leaching followed by hot chlorination. The results indicate that grinding of quartz requires specialist equipment due to the hardness and extreme abrasiveness of the ore leading to additional iron contamination in the ground ore. The critical impurities were aluminium, iron, sodium, potassium, lithium, titanium, zircon, calcium and magnesium. The chemical refining was found effective. The hot chlorination process needed to be done at 1200°C in a chlorine – hydrogen chloride gas atmosphere. The risk of any gas being released during this stage is very serious and only specialist companies should and can carry out this step. More recent studies reported many new options that appear to facilitate the production of HPQ with the requisite purities more easily, but costly equipment along with highly trained operators are required and hence unlikely to become available in standard metallurgical laboratories any time soon.

INTRODUCTION

High purity quartz (HPQ) as a product contains at least 99.99per cent silicon dioxide (SiO_2) as defined by Sibelco, (Sibelco IOTA, 2024; Lines, 2013), which is basis of the internationally recognised quartz products standards. Their IOTA® products are mined from orebodies at Spruce Pine, South Carolina in the USA are used in various high-tech applications including semiconductors for the manufacture of fused quartz crucibles used in the Czochralski (CZ) process, and the production of fused quartz tubing and ingots used to create fabricated quartzware for the semiconductor wafer process. In photovoltaic cells, they are used in the manufacture of crucibles for CZ single crystal silicon growth. In quartz lighting they are used in automotive xenon, halogen, HID and UHP lamps.

The IOTA standard for processed silica is <14 ppm of aluminium, <1.2 ppm of titanium and <0.5 ppm of lithium. Internationally recognised standard for high purity HPQ has required characteristics such as high hardness, low rate of expansion, resistance to high temperatures, high abrasion resistance, high chemical purity, excellent electrical insulator, resistance to thermal shock, resistance to radiation and large transmission of light.

The market is dominated by only a few producers; Quartz Corporation and Sibelco who hold more than 80per cent of the Asia Pacific production. China, Japan, South Korea and Tiawan represent the bulk of the market, along with India as an emerging market for this product. The markets for high purity quartz usage are small but very valuable related predominantly to solar panels, semiconductors, silicon metal and high-tech glass, optics and communication. The Chinese government is expected to spend US$350 billion on clean energy and this will increase demand significantly.

HPQ market

The HPQ market is small but steadily growing. In 2022, it was valued at US$894.6 million. It is estimated to grow at 6.3per cent annually reaching US$1.5 billion (Transparency Market Research, 2004). The general key end uses include the following.

There are other HPQ products with lower level of purities than those of Sibelco IOTA. A summary of classifications, purity levels, estimated market share and indicative prices of HPQ products is shown in Table 1. The data were compiled from various sources including Zang *et al* (2023), Greentech (nd).

TABLE 1

High purity quartz categories.

Classifications	SiO_2 min%	Max impurities (%)	Max impurities (ppm)	Estimated market size (tpa)	Indicative price ($/t)
Standard Purity / HPQ Sand	99.99	0.05	100	0.75	300–600
IOTA Basic / Grade I / Medium Grade HPQ	>99.99 – <99.995	0.003	<100	0.25	500–800
IOTA 4 and 5 / Grade II / Ultrahigh Purity HPQ	≥99.995 – <99.998	0.003	30	<0.1	5–8000
IOTA 8 / Grade III / Hyper HPQ	≥99.998	0.001	10	<0.01	12 000

Microelectronics

The design and microfabrication of very small electronic circuits for use in integrated circuits. The most common are semiconductor transistors at microscopic level. Nano electronics devices down to nanometre levels.

Solar energetics

High purity quartz sand are used in monocrystalline quartz crucibles production. These are crucial components in the manufacturing of photovoltaic cells. These crucibles provide a high-quality environment for growing single crystal silicon ingots used in solar panels. The high purity of the quartz sand ensures optimal performance and efficiency of the PV cells.

Lighting equipment

The IOTA quartz is used to produce quartz lighting including quartz halogen, high intensity discharge (HID) and ultra-high performance (UHP) lamps.

Optics

Fibre optic cables (also called optical fibre cable) are essentially cables made glass that allows the transmission of information as light pulses. These cables are now a common option for ethernet networks and telecom applications due to its high speeds for data transmission across long distances. The production process begins with fibre drawing, where the high purity silica glass is melted and drawn into strands called optical fibres. This process involves carefully controlling the temperature and speed to ensure the fibres have the desired diameter and optical properties.

Some of the applications for Intermediate and High-grade HPQ include optical glass and fused quartz tubing; those for Ultra grade HPQ crucibles for solar applications and high-quality fused glass tubing and quartz ware, and for the Hyper HPQ include semiconductor-grade crucibles and high-end solar semiconductor applications.

METHODS OF PRODUCING HIGH PURITY QUARTZ

Numerous impurities are associated with quartz ores that are suitable for producing HPQ including. Al, B, Ca, Cl, Cu, Fe, Li, Mg, Mn, K, Na, S, Ti Ga, Ge, P, Pb, Nb, Sr, Zn, Zr, Y and even OH^- (Lin *et al,* 2020; Götze, Pan and Müller, 2021; Pan *et al,* 2022; Liu *et al,* 2023; Zang *et al,* 2023). Iron is often the predominant impurity and can exist in various forms. How the impurities are associated with the quartz vary. They can be as interface impurities, fine-grained mineral inclusions, micron-grade fluid inclusions or trace lattice elements (Lin *et al,* 2020). Interface impurities are only physically associated and can easily be removed by washing or leaching once liberated by grinding. Fine-grained inclusions are more difficult to remove as exposing them to leaching cannot be achieved by grinding. High temperature treatment to form micro-cracks for the leachant to reach inclusions or microwave or ultrasonic assisted leaching are among the approaches to remove these impurities. High temperature treatment to allow crystal phase transformation has been used to treat micro-grade fluid inclusions. These differences in the nature of the impurities have resulted in an increasing number of different approaches in removing the impurities from the quartz ore.

It would appear and be a reasonable proposition that producing HPQ from quartz would be straightforward once the nature of the impurities and their association with the quartz ore are identified. Unfortunately, as Götze, Pan and Müller (2021) pointed out, unambiguous detection and characterisation of defect structures in quartz are a technical challenge and can only be successfully realised by a combination of advanced analytical methods such as electron paramagnetic resonance (EPR) spectroscopy, cathodoluminescence (CL) microscopy and spectroscopy as well as spatially resolved trace-element analysis such as laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and secondary-ion mass spectrometry (SIMS). Clearly, many of these analytical techniques are not yet available for routine use even for institutional researchers let alone metallurgical laboratories. In practice therefore, a trial and error of the different approaches remains the only viable option at this stage.

Figure 1 shows a typical HPQ process flow sheet. Overall, the unit process is comparable to any hydrometallurgical process. It is only the specific techniques in the extraction and purifying steps that new approaches are being introduced.

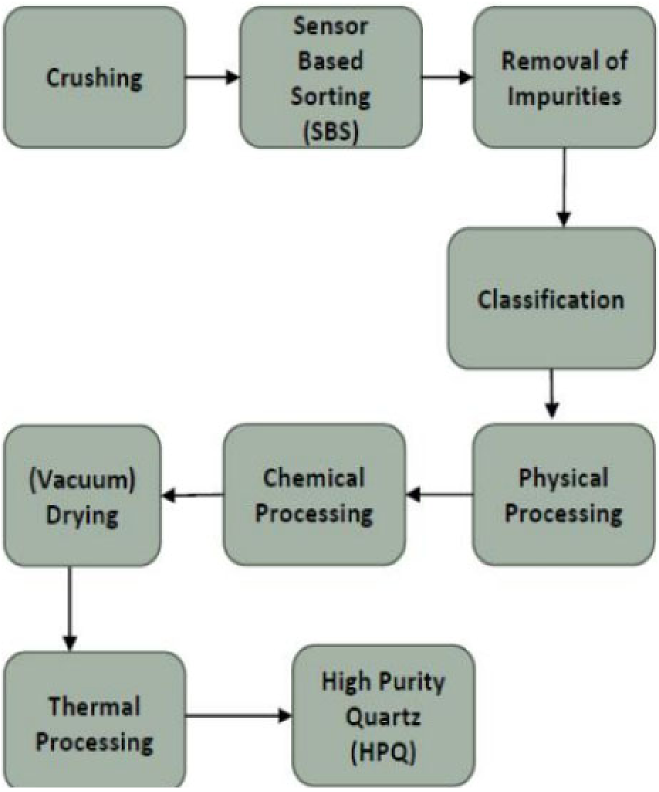


FIG 1 – Typical HPQ process flow sheet.

Crushing and grinding

As with other minerals, crushing and grinding is used in processing quartz to reduce the size of the raw quartz particles, liberate mineral impurities and allow further physical and chemical steps that are needed to separate or dissolve impurities. The classical methods of comminution could introduce contaminants, so either autogenous grinding or electrodynamic fragmentation are required. The former, utilises the material to be ground (quartz lumps) as the grinding media. In contrast to conventional grinding, no wearable parts made of steel or grinding media made of aluminium or zircon oxide are used during autogenous grinding. This way, additional contamination of the quartz material is avoided. The latter on the hand is an enhanced technology that liberates quartz crystals in the composite rock largely without contamination and with a low loss of undersize particles. A high-voltage discharge generates shock waves within the quartz lump causing it to fragment along the weaker natural boundaries between crystals.

Sensor-based sorting

Sensor-based sorting involves the use of technology such Radiometric, Visual Spectrometry, Thermal infrared, and various laser-based techniques (Robben and Wotruba, 2019) to separate ores based on particular characteristics. An example of sensor-based sorting application in quartz is a combination of Tomra laser and Tomra colour sorters to separate the quartz particles according to four qualities: white and light grey quartz with low iron oxide content for engineered stones; grey and yellow quartz for the glass industry; coloured quartz for ferrosilicon used in the metallurgical sector; and coloured gravel, also for ferrosilicon.

Removal of impurities

Scrubbing and washing

Scrubbing cleans up the surface of the quartz and washing removes any soil, clays or non-quartz minerals. Its application in processing quartz ores is similar to those of other commodities.

Magnetic separation

Magnetic separation is used to separate minerals with paramagnetic properties such as iron oxides or heavy minerals. Quartz itself has diamagnetic properties and therefore quartz particles are repelled from the magnetic field. The technique has been used in quartz ore to remove iron present as a magnetic oxide (Pan *et al,* 2022; Liu *et al,* 2023).

Electrostatic separation

This is used to separate particles based on them being conductors or non-conductors in a high voltage discharge. The quartz must be hot and dry and is fed between a positive and negative electrode with a high voltage discharge. The particle will develop a surface charge by induction if placed in an electric field. Conductive particles will lose their negative charges quickly and become positively charged. Non-conductive particles can't dissipate the charge and remain neutral. Electrostatic forces will attract conductor particles to the electrode resulting in a lifting effect. A splitter in the middle of the stream will separate conductors and non-conductors including quartz.

Flotation

Flotation takes advantage of the differences in hydrophobicity of quartz and impurities but does depend on the type of mineral impurity and degree of liberation hence for some quartz ores, it is not beneficial. Investigations are being carried out to address the issue. For example, Larsen and Kleiv (2016) have shown that quartz can be floated selectively from dilute hydrofluoric acid by using only a frother. The use of the technique yielded a feldspar concentrate with 99.9per cent grade with a quartz concentrate of 95.4 percent grade for a recovery of 88.5per cent of the quartz. In another work, Shijie *et al* (2016) found that with some quartz sand ores up to 80per cent is in the fraction size of -482 µm making the use of traditional flotation cell not effective. Consequently, they designed and tested a flotation cell structure with a middled positioned impeller, false bottom and draft tube based on thermodynamic considerations. Pilot testing of their design showed results consistent with their theory giving an alternative flotation method for quartz ore preparation.

Leaching

Leaching is an effective process used to remove impurities. With very rare exception, the removal of impurities to produce high purity quartz always involves a leaching stage. It is usually carried out using solutions of strong mineral acids at elevated temperatures including hydrofluoric, hydrochloric and nitric acid. Hydrofluoric acid is undesirable because of occupational safety and health issues. More recently other leachants such as organic acid micro-organism have been evident. Trace minerals such as feldspars, micas and other minerals are dissolved during leaching. Additionally, impurities can be removed which are in micro fissures and along grain boundaries.

Iron is often the predominant and intractable impurity in quartz. Focusing on its removal, Tuncuk and Akcil (2016) showed that leaching a quartz ore with sulfuric acid together with oxalic acid, citric acid or glucose achieved iron removal of 98.9, 98.0 and 96.5per cent respectively, yielding a quartz product with only 1 ppm, 1.8 ppm and 3.1 ppm respectively of residual iron impurity. They postulated that the organic acids and glucose acted as reducing agents converting the iron (III) oxide in the quartz to the more soluble ferrous sulfate.

Shao *et al* (2022) found that the use of a combination of alkali corrosion and mixed acid leaching was effective in purifying a quartz ore with 99.98per cent SiO_2. The technique involves subjecting the ore to NaOH solution (12per cent) at 200°C for 100 mins followed by mixed acid leaching using a solution of HCl (4M), HNO_3 (1M) and HF (0.25 M) at 200°C for 5 hrs. Assay of the washed and dried residue yielded and HPQ with 99.998per cent SiO_2.

Liu *et al* (2023) reviewed the occurrence and removal of iron from quartz. This work found that iron existed in quartz in various forms, including as iron minerals, lattice impurities and fluid inclusions. The latter quite intractable to remove. They concluded that various techniques could be used to remove the contaminants including conventional pre-treatment methods such as magnetic separation, roasting, flotation, leaching with various acids minerals acids They also found the use of the micro-organisms *Aspergillus niger* and *Mycobacterium phlei* as options for removing iron impurities from quartz.

Other methods

Hot chlorination

In the hot chlorination process quartz is heated to temperatures of up to 1200°C in a chlorine and hydrogen chloride gas atmosphere. Chlorination causes structural impurities to be removed from the crystal lattice into the gas phase. Chlorination is particularly efficient for the reduction of alkali, alkaline earth, and transition metals which are highly restricted in semiconductor applications (ANZAPLAN, nd).

Fluoridation of quartz to produce 5N SiO_2

Dyachenko and Kraydenko (2012) reported a technology for producing 5N silica product from quartz sand. It involves reacting the quartz with ammonium fluoride or ammonium bifluoride (EQ to produce ammonium hexafluorosilicate as shown in Equation s 1 and 2 respectively.

$$SiO_{2(s)} + 6NH_4F_{(s)} \rightarrow (NH_4)_2SiF_{6(s)} + 4NH_{3(aq)} + 2H_2O_{(l)} \quad (1)$$

$$SiO_{2(s)} + 3NH_4F.HF_{(s)} \rightarrow (NH_4)_2SiF_{6(s)} + NH_{3(aq)} + 2H_2O_{(l)} \quad (2)$$

Heating (the ammonium hexafluorosilicate turns it into gaseous state and condensing it and treated with ammonia water produces high purity silica and regeneration the ammonium fluoride (Equation 3).

$$(NH_4)_2SiF_{6(g)} + 4NH_4OH_{(aq)} \rightarrow SiO_{2(s)} + 6NH_4F_{(aq)} + 2H_2O_{(l)} \quad (3)$$

Filtration of the product separates the silica from the ammonium fluoride solution.

Thermal treatment

Thermal treatment (calcination) of high-purity quartz improves its melting behaviour due to the removal of fluid inclusions. If not removed, these inclusions may form bubbles in the final quartz glass, compromising the products' performance. The resulting pressure increase in the inclusions during treatment causes the development of microfractures in quartz particles. Through these fractures, the contained gases, H_2O, and potentially other phases that contribute to bubble formation during later melting can escape (ANZAPLAN, nd).

The use of microwave heating has been found to rupture fluid phase inclusions in the crystal rendering the impurities leachable or washable in the case of soluble impurities (Pan *et al,* 2022).

Khalifa *et al* (2019) found that annealing a natural sand silica sample with 97.72per cent SiO_2 at 1000°C using an infrared furnace for 1 hr under N_2/O_2 atmosphere and then soaking the product in HF (5per cent) and HCl (4per cent) solution at 1:7 volume fraction yielded a silica product with 99.9per cent purity.

Du *et al* (2021) showed that reductive roasting pre-treatment of natural quartz powder (NPQ) at 400–500°C in the presence of ammonium sulfate as reducing agent prior to leaching, achieved reduction of the iron impurity from 145 ug/g of NPQ to below 0.3 µg/g NPQ compared to straight leaching only. They postulated that the technique reduced the iron from iron (III) oxide to iron (II), which is more soluble and hence more responsive to leaching.

Upgraded silicon

Polycrystalline silicon, or multicrystalline silicon, also called polysilicon, poly-Si, or mc-Si, is a high purity, polycrystalline form of silicon, used as a raw material by the solar photovoltaic and electronics industry. Polysilicon is produced from metallurgical grade silicon by a chemical purification process, called the Siemens process. This process involves distillation of volatile silicon compounds, and their decomposition into silicon at high temperatures. When produced for the electronics industry, polysilicon contains impurity levels of less than one part per billion (ppb).

The polysilicon feedstock consisting of large rods, usually broken into chunks of specific sizes and packaged in clean rooms before shipment, is directly cast into multicrystalline ingots or submitted to a recrystallisation process to grow single crystal boules. The boules are then sliced into thin silicon wafers and used for the production of solar cells, integrated circuits and other semiconductor devices.

METALLURGICAL TEST WORK RESULTS

Materials and methods

The quartz ore sample was taken from Muckinbudin approximately 250 km east of Perth, Western Australia, where there is a large pegmatite dyke (feldspar) that has been mined previously. Adjacent to this is a quartz reef running parallel with an adjacent dyke. Figure 2 shows an exposed quartz reef. The quartz has not previously been exploited.

FIG 2 – Exposed quartz reef.

A bulk sample of rock pieces from the quartz reef was selected and despatched to ALS Perth, where the test work was performed but managed by METS Engineering.

The ore was crushed and crushing work index, bond ball mill work index (BWI) and abrasion index (AI) were determined. A head assay was carried out. Grind establishment to P_{80} 106 was carried out before undertaking wet high intensity magnetic (WHIMS) separation and flotation. The beneficiated ore was then subjected to hot acid leaching using various acids including their mixtures under various leaching conditions. After the leaching, the slurry was filtered, the silica solid was washed, dried and assayed.

Results and discussion

The results of the metallurgical tests are summarised in Table 2.

TABLE 2

Test work results.

Test	Result	Unit
Specific gravity	2.54	
Crushing work index (CWI)	7.2	kWh/t
Bond abrasion index (BAI)	0.1498	
Bond ball mill work index (BWI)	19.5	kWh/t
Head assay of raw ore	99.98	%
Magnetic separation	99.91	%
Flotation recovery	99.86	%
Highest purity of SiO_2 generated after acid leaching	99.98	%

The crushing work index (7.2) is a relatively low value; the bond abrasion index (0.1498) was a modest value and the bond ball mill work index (19.5) was high.

The head assay (99.98per cent) clearly indicate that the quartz ore was of very high-grade, which is consistent with its appearance as shown in Figure 3. The two pieces are typical of the bulk sample. It is potentially a source of more than basic purity HPQ, which is yet to be established.

FIG 3 – Raw quartz samples.

The lower purity of concentrate after magnetic separation was owing to an increase in the iron contamination. This contamination was traced to the use of a standard laboratory crusher for crushing and a steel rod mill for grinding. Clearly, the use of laboratory conventional crusher and grinder is a significant issue. Other methods, such as the use of autogenous grinding or electrodynamic fragmentation are being explored in the continuation of this work.

The leaching conditions that yielded the product with the highest purity achieved to date (99.98per cent) were using HCl at 80°C for 12 hrs. Determination of exact purities, ie percentage up to three decimal places, is yet to be completed. Assay of the high purity quartz products is not routine in standard metallurgical laboratories.

The higher purity of the quartz after leaching compared to that after magnetic separation indicates the contamination from comminution was at least partly removed in the leaching step. Still, the purity achieved to date is clearly no better than that of the feed owing to uncertainty in measurement. It is however apparent that the use of microwave digestion or infrared furnace and other techniques as adjuncts to leaching that have been shown to improve the removal of the impurities are necessary. Easy access to multi-quad inductively coupled plasma mass spectrometer that allow achievement of detection limits down to parts per trillion level would be helpful. So are analytical techniques mentioned elsewhere in this paper that would allow not only the identification but also characterisation of the impurities of the quartz ore feed as this would avoid the guesswork in choosing the appropriate approach in each of the unit processes.

The work to improve the purity of the products at every step of the process including their replication is in-progress.

CONCLUSIONS

High-purity Silica is a high-grade (>99.99per cent Silicon dioxide (SiO_2)), raw ingredient used for semiconductors in electronics, computer processors, photovoltaics (solar panels), optical fibres, high performance ceramics and specialty glass applications. It is relatively rare in nature and regarded as a critical mineral.

The physical methods of separation achieved very little in the removal of impurities although the final value is yet to be received. The chemical separation processes including leaching was effective. This is understandable as quartz ore was of very high purity and thus, magnetic separation and flotation achieved very little. Hence, the focus should be on further improvement in the chemical separation processes.

For Australian operations the processing by crushing and grinding followed by hot acid leaching is achievable but processing beyond this includes the use of specialised equipment requiring highly trained operators and proprietary knowledge and is easier undertaken overseas, at least for now.

The global decarbonisation is predicted to see a significant, perhaps accelerated, demand for HPQ due to the rapid uptake of solar panels around the world.

ACKNOWLEDGEMENTS

The author would like to thank the AusIMM and METS Engineering Group for permission to publish this paper and all colleagues and engineers at various sites, METS staff and other consultants for their contribution and the management of METS for their permission and constructive criticism of various drafts of this presentation. Thanks also to various vendors for providing technical input.

REFERENCES

ANZAPLAN, nd. High Purity Quartz [online]. Available from: <https://www.anzaplan.com/minerals/high-purity-quartz/> [Accessed: 14 August 2024].

Dyachenko, A and Kraydenko, R, 2012. Technology of high purity silicon dioxide production, in *Proceedings of the 51st Annual Conference of Metallurgists of CIM (COM 2012)*, pp 237–249 (Met Soc: Niagara Falls).

Du, X, Yang, D, Zheng, S, Sun, Z and Li, C, 2021. Deep Insight into the Reductive Roasting Treatment on Iron Removing from Quartz, *Advanced Powder Technology*, 32(12):4825–4832.

Götze, J, Pan, Y and Müller, A, 2021. Mineralogy and mineral chemistry of quartz: A review, *Mineralogical Magazine*, 85:639–664.

Greentech, nd. Background to HPQ [online]. Available from: <https://greentechminerals.com.au/our-resource/description/> [Accessed: 12 April 2024].

Khalifa, M, Ouertani, R, Hajji, M and Ezzaouia, H, 2019. Innovative technology for the production of high-purity sand silica by thermal treatment and acid leaching process, *Hydrometallurgy*, 185:204–209.

Larsen, E and Kleive, R A, 2016. Flotation of quartz from quartz-feldspar mixtures by the HF method, *Minerals Engineering,* 98:49–51.

Lin, M, Liu, Z, Wei, Y, Liu, B, Meng, Y, Qiu, H, Lei, H, Zhang, X and Li, Y, 2020 A Critical Review on the Mineralogy and Processing for High-Grade Quartz, *Mining, Metallurgy and Exploration*, 37:1627–1639.

Lines, M, 2013. Key uses and growth markets for high purity quartz, Presentation in Chinese Industrial Minerals & Markets, Roundtable, Shanghai, September 2013.

Liu, C, Wang, W, Wang, H, Zhu, C and Ren, B, 2023. A Review on Removal of Iron Impurities from Quartz Mineral, *Minerals*, 23:1128; 21 p.

Pan, X, Li, S, Li, Y, Guo, P, Zhao, X and Cai, Y, 2022. Resource, characteristic, purification and application of quartz: a review, *Minerals Engineering*, 183:107600; 20 p.

Robben, C and Wotruba, H, 2019. Sensor-based ore sorting technology in mining—Past, present and future, *Minerals*, 9:523.

Shao, H, Zang, F, Ji, M and Yu, M, 2022. Prepare and Mechanism of High Purity Quartz by Alkali Corrosion and Acid Leaching Process Using Vein Quartz, *Silicon,* 14:12475–12483.

Shijie, L, Ming, T, Tianran, F, Zhengchang, S and Zhibin, H, 2016. Design of Special Flotation Equipment for High Purity Quartz Sand, *Canadian Institute of Mining, Metallurgy and Petroleum*, 8 p.

Sibelco IOTA, 2024. High purity quartz products and their uses [online]. Available from: <https://www.sibelco.com/en/materials/high-purity-quartz> [Accessed: 12 April 2024].

Transparency Market Research, 2004. High purity quartz market [online]. Available from: <https://www.transparency marketresearch.com/high-purity-quartz-market.html> [Accessed: 12 April 2024].

Tuncuk, A and Akcil, A, 2016. Iron removal in production of purified quartz by hydrometallurgical process, *International Journal of Mineral Processing*, 153:44–50.

Zhang, R, Tang, C, Ni, W, Yuan, J, Zhou, Y and Liu, X, 2023. Research status and challenges of high-purity quartz processing technology from a mineralogical perspective in China, *Minerals*, 13:1505.

High purity alumina and potash produced from feldspar

D Connelly[1]

1. Principal Consulting Engineer, METS Engineering Group, West Perth 6872.
   Email: damian.connelly@metsengineering.com

ABSTRACT

High purity alumina (HPA) is a processed, premium non-metallurgical alumina product characterised by its purity level ie 99.99 per cent (4N) or 99.999 per cent (5N). The market price, application, and performance of HPA varies widely according to its degree of purity. High purity alumina is a form of aluminium oxide (Al_2O_3) with growing use in LED lighting and coating on the ceramic cathode separator sheets in lithium ion batteries.

This paper describes a study on producing high purity alumina from feldspar to produce HPA and potash for use as a fertiliser. The project was positive for a number of reasons. High potassium extraction (>99 per cent) was achieved in the alkali leach using sodium hydroxide as the leaching agent and full dissolution of the alkali leach residue was achieved using hydrochloric and sulfuric acid. The potential to produce a high purity alumina product via a complex but promising emerging process was assessed. The potential to extract potassium as potassium sulfate to add value to the project was also demonstrated with the test work.

INTRODUCTION

Aims and objectives

The purpose of this technical paper is to present the results of the Scoping Study for extraction of potash from K-feldspar. This report presents three main processing options with one of them selected for assessment of its technical and economic viability. Additionally, this report gives recommendations on further work to enhance the accuracy of any claims made to complete the study and better assess the viability of the project.

Deposit and location

The Mukinbudin feldspar deposit is located in Western Australia. The deposit lies approximately 290 km east north-east of Perth and is located 7 km north-west of the closest town Mukinbudin and 65 km north of the Great Eastern Highway (Figure 1). The mine is situated on Koorda-Bullfinch Road which connects to the Great Eastern Highway via roads suitable for truck transportation.

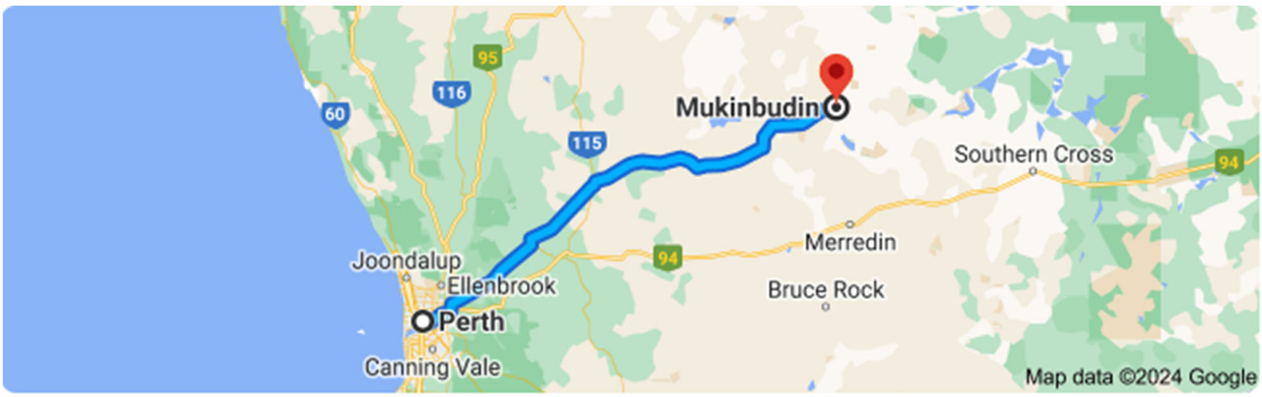


FIG 1 – Location of Mukinbudin.

The deposit is located in the shire of Mukinbudin which is situated in the North-eastern Wheatbelt. The local economy is predominantly based around agriculture. Mukinbudin itself has a population of 450 people with shops and a hotel.

The Mukinbudin feldspar mine was historically mined for glass applications although there has been no activity at the mine since 1997.

Climate

The Mukinbudin feldspar deposit is located close to the coast of Western Australia and as such still receives a large amount of rainfall every year averaging 300 mm. The pan evaporation rate for this area is estimated at 2400 mm/a. This is low when compared to current proposed potash mining operations employing evaporative ponds for crystallisation such as Kalium Lakes (3800 mm/a) or Australian Potash (3200 mm/a). The temperature has reached mid-40s in the past summer.

History

Exploratory drilling was conducted in the area sometime before 1970. Initially quartz was mined from this location by Snowstone Pty Ltd. They mined quartz until 1979 until Matlock Mining purchased the mine in 1980. Commercial Minerals Ltd purchased the mine in 1988 and switched to mining feldspar. The mine was closed in 1997 and no operation has been conducted there since. The mine was once the second largest producer of feldspar in Western Australia.

METALLURGICAL TEST WORK

Mineralogy

X-Ray Diffraction was used to determine the mineralogy of the feldspar sample. METS sent the fine fraction of the feldspar ore to Microanalysis Australia for a semi-quantitative X-Ray Diffraction (XRD) analysis. An XRD identifies the crystals present in the sample. Quantitative analysis reveals the composition of each of these crystal fractions. XRD is limited to crystalline solid. So, composition of the any amorphous (non-crystalline) material in the sample was not known. The X-ray source was cobalt-60. The phases present in the sample can be seen in Table 1.

TABLE 1

Crystalline phases and their concentration in the sample.

Mineral phase	Concentration (%)	ICDD match probability
Microcline ($KAlSi_3O_8$)	79	good
Albite ($Na_{0.986}Al_{1.005}Si_{2.995}O_8$)	18	good
Muscovite-2M#1 ($KAl_2(Si_3Al)O_{10}(OH,F)_2$)	3	medium
Quartz, syn (SiO_2)	trace	medium
Kaolinite-1A($Al_2Si_2O_5(OH)_4$)	trace	

The ICDD match probability is an indication as to how well the peak positions of the XRD match those in published literature for each compound.

Microcline contains primarily potassium and aluminium, which are the valuable elements in the ore. So, its high value is a favourable outcome. The high amount of albite is unfavourable to the process, as it essentially a gangue mineral and thus, reducing the quality of the feed and decreasing the percentage of reagents that is utilised effectively. In spite of this, the very high microcline fraction makes this Mukinbudin feldspar high-grade compared to many other feldspar deposits making the deposit better suited for potassium extraction.

X-Ray fluorescence

The purpose of the X-Ray Fluorescence (XRF) tests was to determine the elemental composition of the sample. Head assays were conducted on three fractions of the bulk sample collected from

Mukinbudin. These were 'fine', 'coarse' and 'rock'. The composition of the samples can be viewed in Table 2.

TABLE 2

Composition of the bulk K- Feldspar sample.

Sample	Al	Ca	Fe	K	Mg	Mn	Na	P	Si
Bulk fine	9.48	0.072	0.287	9.48	0.009	0.008	2.11	<0.001	30.88
Bulk coarse	9.45	0.068	0.227	10.07	0.004	0.005	1.98	<0.001	30.68
Rock	9.72	0.076	0.143	10.21	<0.001	0.004	2.279	<0.001	30.45

The XRF results are in good agreement with the XRD data. The sodium composition is accounted for by the albite in the sample and the presence of potassium is mainly attributed to its presence in microcline. It is also of note that the sample contains substantial iron making it the major contaminant of the product of the alumina product following downstream processing.

Sighter leaching tests

The sighter test work for potash extraction from the feldspar identified one promising option. This was a high temperature 'bake' with caustic soda (NaOH) at high per cent solids. The amenability of the feldspar to direct atmospheric acid leaching was also trialled with some success (Türk *et al*, 2021; p 7). The purpose of the work reported in this paper was to build on this results on that and possibly present some other options such as roasting (Mete and Huseyin, 2019; p 7).

It is well known that many silicates are refractory to acid leaching even at high temperature and pressure and this K-feldspar deposit proved no different (Casey, Westrich and Holden, 1991; p 212). The test work programme, conducted as part of this study, focused on the use of alkali reagents for leaching of the feldspar to produce a solution containing the potassium and a solid residue containing the aluminium. Several options, including high temperature pyrometallurgical molten salt processes were considered (Kumanan *et al*, 2016). Ultimately, however, METS pursued a hydrometallurgical route using NaOH and $Ca(OH)_2$ as the leaching agents. This decision to not test the molten salt process was made in part due to the success with caustic leaching in previous test work and also due to METS perception that a molten salt process would have higher energy costs than a hydrometallurgical process and make extraction of aluminium more difficult.

For the leach test work, it was deemed necessary to reduce the particle size of the feldspar. This increases the surface area available for the dissolution reaction to take place improving the reaction kinetics (Dhawan and Agrawal, 2022).

The feldspar was pulverised using a Braun Disc Pulveriser at the CSIRO sample preparation facilities and a particle size distribution (PSD) of the ground product was established. The PSD data for the ground product is shown in Table 3.

TABLE 3

PSD for ground feldspar.

Screen size (µm)	Mass (g)	% Mass	Cumulative % retained	Cumulative % passing
106	57.4	38	38	62
75	26.0	17	55	45
53	32.6	21	76	24
45	4.89	3	79	21
38	9.67	6	86	14
-38	21.7	14	100	0

Initial leaching tests

The leaches were conducted at atmospheric pressure in a beaker using a hot plate to adjustment of the temperature of the solution or paste. For leaches that required stirring, a magnetic stirrer was used to agitate the slurry. The pulverised material shown in Table 3 was used for the tests, which did not involve screening out any oversize material. The extractions for each leach can be seen in Table 4.

TABLE 4

Sighter leach test work summary.

Test	Leaching agent	Leach type	Extraction					
			Al	Ca	Fe	K	Na	Si
LT1	H_2SO_4	B+WL	9.3%	19.5%	78.8%	11.1%	3.0%	6.1%
LT2	HCl	L	8.6%	22.7%	72.7%	9.2%	5.4%	7.0%
LT4	NaOH	L	30.0%	-2.1%	46.3%	30.8%	26.3%	26.8%
LT5	NaOH	B+WL	45.8%	-142.7%	-30.2%	93.1%	-146.1%	79.7%

B – Bake (high per cent solids paste, high temperature). WL – Water Leach (follows a bake, dissolves solubilised elements). L – Leach (low per cent solids slurry).

Extraction of both potassium and aluminium using acids is shown to be very low. The purpose of the acid leach tests was to extract the potassium and aluminium with minimal dissolution of the silicates. This approach proved to be ineffective in the conditions used for our tests so the use of an alkali reagent to attack the silicate matrix was then trialled.

Both, a leach at ~10 per cent solids and a bake were trialled using caustic to attack the silicate matrix (LT4 and LT5 respectively). Aluminium extraction and potassium extraction were notably higher than those obtained from acid leach tests with a maximum potassium extraction of 93 per cent achieved in LT5.

The high potassium extraction achieved in LT5 proved to be promising and warranted further investigation. A particular concern with this process moving forward is the solution formed with the water leach. The high viscosity would prove very difficult to manage on an industrial scale. An investigation revealed that a hydrothermal (elevated temperature and pressure) process may overcome this problem by producing different products. CSIRO were approached to assist with these tests due to their technical expertise and facilities capable of performing the tests.

CSIRO leach test work

CSIRO and METS developed a test plan to extract potassium from feldspar. The test plan involved two leach tests using sodium hydroxide and lime as leaching agents. Both tests were conducted in an autoclave at elevated temperature and pressure.

The following is a summary of the work conducted including the important conclusions that have been drawn from the results.

Sample preparation and experimental conditions

The feldspar samples for the alkali leach test work to be conducted by CSIRO were too coarse. To prepare the sample to the desired passing size of 75 µm, METS ground ~15 kg of the feldspar acquired from the Mukinbudin site was ground using a rod mill. The ground feldspar was then dry screened by CSIRO to produce a -75 µm feed for alkali leaching. The composition of the -75 µm fraction of the ground feldspar can be seen in Table 5.

TABLE 5

Assay of feldspar leach feed.

Sample	Al	Ca	Fe	K	Mg	Mn	Na	P	Si
-75 µm	9.99%	0.08%	0.57%	8.93%	0.01%	0.01%	2.28%	0.01%	31.5%

The leaching tests were undertaken in Parr autoclaves fitted with dual pitch-blade impellers and a serpentine coiling coil. The tests were conducted with the following conditions:

- Test 1, Lime: 10 per cent w/w K-feldspar ore in water with lime added to give Ca/(Al+Si) molar ratio of 1.25, heated to 260°C and run for a further 10 hr before cooling and disassembly. A 1 galon 316 stainless steel vessel was used for this test with samples taken at 0, 60, 120, 240, 360, 480 and 570 mins.
- Test 2, NaOH: 10 per cent w/w K-feldspar ore in 8.5 M NaOH solution heated to 260°C and run for a further 4 hr before cooling and disassembly. A 2 L Inconel 600 vessel was used for this test with samples taken at 0, 30, 60, 120, 180 and 240 mins.

The samples were vacuum filtered using a 0.45 µm Supor membrane to obtain primary filtrate for analysis. Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) was used to analyse both the solids and liquids with solids first fused with 12:22 lithium tetraborate-lithium metaborate and dissolved in deionised water.

Results

The extractions for each leach test are given in Table 6. These are given on the basis of extraction liquid and solids during the experiments. If the final flushed contents of the autoclave were also included, the calculated extractions could change marginally and thus, minimal impact on the analysis.

TABLE 6

Extractions (%) of major elements from K-feldspar.

Test #	Al	Ca	Fe	K	Mg	Mn	Na	P	Si
Test 1	0.1	0.1	0.1	65.3	0.2	5.1	92.6	3.2	0.0
Test 2	3.9	2.1	22.5	99.3	4.2	22.4	91.7	25.9	51.7

Difficulties were experienced with the first leach test. The formation of a semi-solid mass (Figure 2) meant it was not possible to sample the autoclave contents after an hour and as such any samples taken from the autoclave after that time were not deemed representative. Extractions of 65.3 per cent and 92.6 per cent of potassium and sodium respectively were achieved. The solid residue in the autoclave was found to contain mostly tobermorite and kaotite using XRD.

FIG 2 – Solid mass formed during Test 1 sticking to the autoclave impellers.

The second leach test did not experience the same difficulties as those experienced as those of Test and sampling had no issues. Extractions of 99.3 per cent, 51.7 per cent and 3.9 per cent of K, Si and Al respectively were achieved. XRD analysis showed that the solid residue contained hydroxycancrinite and hydroxysodalite.

The Tests 1 and 2 sample solutions that were withdrawn from the autoclave periodically are shown in Figure 3. The Test 1 leach solutions are markedly clearer than those of Test 2. This difference in colour is likely due to much higher iron extraction in Test 2.

FIG 3 – Left- Leach solutions for Test 1; Right – Leach solutions for Test 2.

Acid leaching of the alkali leach residue

Although Al is amphoteric, an acid attack is far stronger in breaking down minerals than alkali. So, the residue from the alkali leach was subjected to acid leaching to extract the aluminium: one using HCl and one using H_2SO_4. Nitric acid is likely also be effective too but it is more expensive and it is known that it has more issues associated with its handling and use in chemical processing.

Table 7 shows the composition of the alkali leach residue that was fed into the acid leaching tests.

TABLE 7

Leach residue composition (%).

Leach Residue	Al	Ca	Fe	K	Na	Si
Test 1: Tobermorite	9.60	0.07	0.44	0.06	0.19	15.22
Test 2: Sodalite/Cancrinite	19.92	0.15	0.38	0.17	5.02	32.12

The leaching conditions for each acid leach test is summarised in Table 8. In all tests, the alkali leach residue was added to the acid solution and given an initial brief shake to ensure all the solids were submersed in the leach solution. Dissolution reactions were apparently occurring vigorously without mechanical agitation. Within 10 mins there were no more visible solids in the cancrinite and sodalite leach.

TABLE 8

Acid leach leaching conditions and observations.

Residue	Acid	Residue mass (g)	Solids (%)	Acid conc (%)	Observations
Tobermorite	HCl (32%)	9.9	9.8	11.8	Solution reacted quickly, evolved a gas and changed colour to yellow/brown, white 'fluffy' solids suspended in solution
Tobermorite	H_2SO_4	10.3	10.2	11.4	Solution reacted quickly, evolved a gas, white solids formed
Cancrinite/Sodalite	HCl (32%)	2.9	9.7	11.4	Solution reacted quickly, forming a yellow/brown solution
Cancrinite/Sodalite	H_2SO_4	3.0	9.7	11.6	Solution reaction quickly, forming a green/yellow solution

Solids did remain in the solution for both the HCl leach and H_2SO_4 leach of the tobermorite. The suspended solids in the HCl leach solution were found to be most likely silica. The H_2SO_4 leach residue was comparable in mass to the initial feed for the tobermorite residue leach. A large mass of solids were expected to remain after this leach due to the high calcium content of the tobermorite, which could be attributed to the formation gypsum precipitate.

The viscosities of all the solutions were comparable to that of water after an hour. The solutions were left overnight to see if residence time affected the precipitation of silica. The cancrinite/sodalite residue formed a gelatinous semi-solid form in both cases, which is typical silica colloids formation. Upon drying, crystals formed from both leach products.

The tobermorite leach solutions when left overnight behaved differently to the cancrinite/sodalite leach solutions. The H_2SO_4 leach product maintained its low viscosity suggesting silica precipitated along with the gypsum. The HCl leach product increased in viscosity but only partially formed a semi-solid gel. More work is required to optimised the leaching conditions to allow the formation of a filterable silica product. For obvious practical purposes, it is desirable to precipitate almost all silica out of the solution within the acid leach reactor without lengthy residence times.

ANALYSIS

An important criterion for analysing these results is the movement of aluminium and potassium between solid and solution. It is desirable to extract the potassium from the K-feldspar into the leach solution while the aluminium remains in its solid state. This allows potassium to be extracted individually from aluminium, removing the need to separate the potassium from the aluminium downstream. The effect of using KOH leach which was not attempted this test work.

Lime leach

The lime leach produced a very clean solution consisting mostly of potassium, sodium and calcium and only minimal silicon. This minimal dissolved silicon simplified the downstream purifying step. This is a distinct advantage lime leach over the caustic leach. The main concern with this test was the formation of the semi-solid mass. There are no established processes that is capable of managing this effectively on an industrial scale. The extraction of potassium at 65.3 per cent was lower than expected. Several papers have shown that extractions in excess of 90 per cent are achievable but are silent on whether they observed a similar semi-solid mass formation as observed in the present work.

The aluminium extraction was very low at only 0.1 per cent. With almost all of the feldspar's original aluminium content contained in the residue, almost no aluminium is lost to potash processing. It is notable that aluminium extraction in the caustic leach was higher (3.9 per cent), in this respect the lime leach performed better. This value (3.9 per cent) is still relatively low such that substantial improvement is likely to be achieved in the process optimisation stage. Aluminium can be easily extracted from the leach residue using an acid leaching process.

Perhaps the biggest concern for this process, considering that production of an aluminium product is essential for the overall process to be viable, is the large percentage of calcium that enters the solid mass from the leach solution. Too much calcium in the solid residue will greatly increase the acid requirements to extract the aluminium. The residual acid in the leach is considered consumed, as the regeneration and recovery of HCl or H_2SO_4 from $CaCl_2$ and $CaSO_4$ (the respective products for leaching with HCl and H_2SO_4) is very difficult and is not expected to be cheaper than simply disposing of the leach solution and replacing the HCl and H_2SO_4.

The formation of the solid mass in the autoclave tells us that the process needs to be adjusted to be feasible. For the purpose of our report we have assumed that a lower solids concentration will be sufficient to solve this problem. In reality the key process parameters will require adjustment such as the Ca/(Al+Si) molar ratio to realise a more successful leach. Decreasing the amount of solids in the reactor is undesirable, as it greatly increase the energy requirements and capital costs due to increased equipment size. If any future work was conducted for the lime leach, it is essential to address these issues in the early stage.

It is however positive that an extraction of 65.3 per cent was achieved in the first sighter leach of K-feldspar. The clean pregnant solution that is produced is also highly promising, as it indicates that the downstream processing is more feasible. With optimisation it is likely that higher extraction can be consistently achieved.

Caustic leach

The caustic leach was far more successful than the lime leach achieving up to 99.3 per cent potassium extraction (Table 6) with minimal aluminium extraction (3.9 per cent) but high silica extraction (51.7 per cent). Potassium extraction was at 98 per cent by the time the autoclave achieved temperature and pressure. This process took ~67 mins. This leaves considerable room for adjusting the residence time in the autoclave. As the potassium extraction was highly effective, it is likely that the residence time required in the autoclave is far less than the two hr residence time for the experiment. The only benefit of using longer residence time is it allows the reprecipitation of the dissolved silicon.

Benchmark projects

There are no benchmark projects to compare this with only molten salt extraction of potassium by the University of South Australia and Centrex Minerals Ltd.

CONCLUSIONS

The lime leach

- Achieved 65.3 per cent potassium extraction with only 0.1 per cent aluminium co-extraction and 0.1 per cent silicon extraction.
- Produced an acid leachable residue for aluminium recovery.
- Formation of a semi-solid mass in the reactor is unfeasible for an industrial scale process.
- Solution produced shows no discolouration.

- Likely requires more work to achieve an optimised extraction process with no guarantee that it will be viable on an industrial scale.

Caustic leach

- Achieved 99.3 per cent potassium extraction with 3.9 per cent aluminium extraction and 51.7 per cent silicon extraction.
- Achieved 98 per cent potassium extraction before the autoclave achieved temperature and pressure. This process took 68 mins.
- Produced an acid leachable residue.
- Solution produced is brown likely due to the presence of iron.
- Requires optimisation with a focus on reducing residence time, increasing solids concentration and minimising NaOH usage.
- Aluminium and silicon extractions decreased with increased time in the reactor suggesting that they reported back into the solids after initial leaching into solution.

PROCESS DESIGN AND OPTIONS ANALYSIS

Given the results from the alkali leach, three distinctly different processing options were considered. These were centralised around the use of leaching reagent, which greatly impacts downstream processing. The three leaching agents considered here were:

- NaOH
- $Ca(OH)_2$
- KOH.

KOH is also considered in the design and options analysis despite not being included in the hydrothermal leaching program. The effectiveness of KOH and NaOH as leaching agents for the extraction of potassium are very similar; this is well documented in prior studies. For the purpose of this analysis, METS have assumed that KOH will perform well when leaching the feldspar by analogy to the very good performance of the NaOH leach. We can therefore produce potassium chloride and HPA.

Option 1 – NaOH leach

This is the selected processing option. The full process description can be seen in Option 3, which is similar.

Option 2 – Lime leach

Brief process description

The feldspar is mined at Mukinbudin and stored on a ROM pad where it is transferred to a ROM bin via a front end loader. The mined feldspar is fed from the ROM bin into a tertiary crushing circuit designed to reduce the size of the feldspar to feed the grinding process (Figure 4). The ROM ore is passed over a grizzly, where undersize particles bypass the jaw crusher. The oversize is then fed via an apron feeder to a primary jaw crusher. The primary crusher is a jaw crusher in open circuit. The product from the jaw crusher and the undersize from the grizzly are conveyed to a single deck screen. The oversize from the screen feeds a cone crusher which is also in open circuit. The product from the first cone crusher feeds a second single deck screen from which the oversize reports to the tertiary cone crusher. The tertiary crusher is a cone crusher in closed circuit with the secondary screen. The undersize from the first and secondary screen are combined in a stockpile where it undergoes loading and transportation to Kwinana.

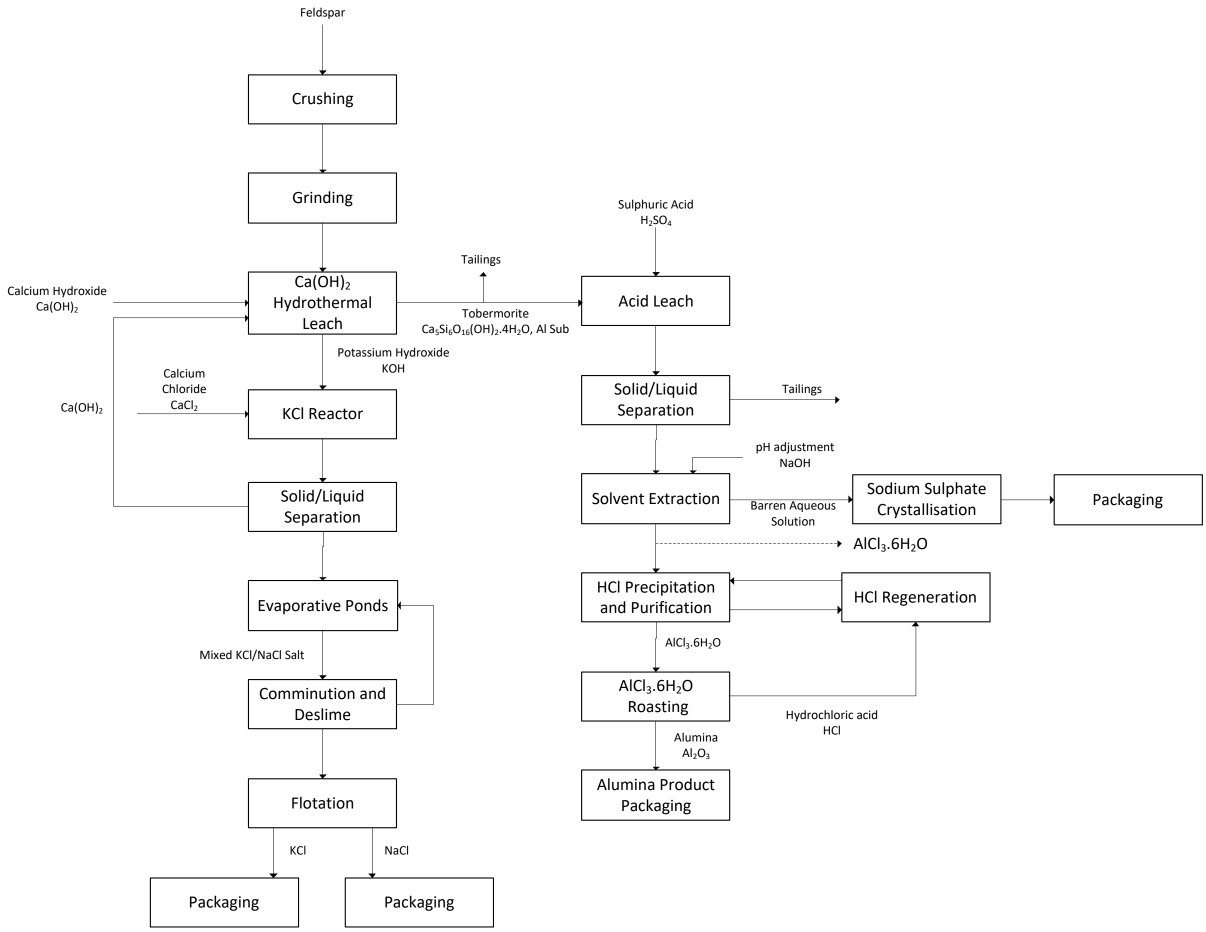


FIG 4 – Block flow diagram for proposed lime process.

The grinding circuit consists of a ball mill in closed circuit with an array of hydrocyclones. The hydrocyclone classifies the ground ore to have an overflow at 80 per cent passing (P_{80}) 75 µm. The underflow is recirculated back to the ball mill for further size reduction. The overflow reports to the lime mixing tank where it is mixed with the lime to give a set concentration for the autoclave reactor.

The lime leach autoclave has a solids density of 5 per cent w/w and operates at a temperature of 260°C and typical residence time of 8 hrs. The slurry discharge from the autoclave feeds a flash vessel which reduces the pressure of the process stream and produces steam which is used to heat the feed to the autoclave. The slurry, now cooled, is thickened and filtered to produce a residue with 90 per cent w/w solids and a solution containing sodium hydroxide and potassium hydroxide. The residue is transported from Mukinbudin to Kwinana for alumina processing.

The residue from the lime leach is acid leached using a concentrated sulfuric acid solution. The concentrated sulfuric acid will solubilise any iron, sodium and aluminium present in the residue, while separating the very high calcium content by precipitation of gypsum. The silica precipitates along with the calcium sulfate. The slurry from the acid leach is filtered and the gypsum and silica mixed solid is neutralised before disposal to tailings.

The solution from the acid leach enters a solvent extraction circuit, where aluminium and iron are separated from the sodium in the feed. The organic containing aluminium and iron is then stripped using a concentrated hydrochloric acid solution. The concentration of hydrochloric acid is raised by sparging the solution with hydrochloric acid gas, precipitating the aluminium chloride from solution as aluminium chloride hydrate (ACH). The impure ACH is centrifuged and redissolved in high purity water before sparging with hydrochloric acid gas yet again to re-precipitate ACH with higher purity. This is again redissolved and re-precipitated to increase the purity further. The slurry containing the high purity ACH is filtered before feeding a roaster which operates at 700°C converting approximately 75 per cent of the ACH to high purity alumina. The roaster product is then fed to a calciner, which operates at 1100°C, converting the remaining ACH to alumina, to give a 99.99 per cent alumina product. The product is then cooled before packaging (Smith and Power, 2022; p 747).

The barren aqueous solution from solvent extraction contains a high concentration of sodium sulfate which can optionally be crystallised using evaporative crystallisation to produce a saleable product.

The potassium-bearing alkali solution from the autoclave is reacted with solid calcium chloride in a stirred reactor to produce a potassium chloride solution and hydrated lime, or, carbonated by carbon dioxide and reacted in a stirred tank reactor with gypsum to produce a potassium sulfate solution. Both solutions contain significant sodium content. The solutions are pumped to crystallisation ponds where they first undergo staged crystallisation (Fujiwara *et al*, 2007; p 2). The solution is initially pumped to a pre-concentration pond. From the pre-concentration pond it enters the crystallisation ponds. The ponds are set-up to be at various stages of the crystallisation process. Some ponds will be inactive at times of the year to allow for harvesting with a salt harvester.

The harvested salt containing a mix of potassium and sodium salts (chloride or sulfate) is crushed in a rotating cage mill to separate potassium salts from any intergrown crystals for flotation. The crystals are mixed with saturated salt solution and deslimed to remove fines and dust. From here the feed enters a flotation circuit consisting of rougher and cleaner flotation cells. The potassium salts are floated from the sodium salts to produce a potassium chloride or potassium sulfate product. The sinks are also processed to form a low-grade sodium chloride or sodium sulfate.

The excess alkali leach residue is transported to the Mukinbudin site for disposal. If the sodium chloride or sodium sulfate produced is of insufficient quality to sell it will also require proper disposal. Disposal of sodium chloride requires a thorough investigation due to complications with the high chloride content. Sodium sulfate would be disposed at the Mukinbudin site along with the other solid waste products. The silica and gypsum mixed precipitate is disposed of on-site with the other solid waste products.

Option 3 – KOH leach

A potassium hydroxide leach is not dissimilar in reactivity to a sodium hydroxide leach. The primary difference between the two is the reaction product. A potassium hydroxide leach will react to form kalsilite ($KAlSiO_4$). The kalsilite is more reactive than the starting feldspar mineral, making it amenable to acid leaching. The biggest difference between the processes is that the potassium reports to the leach residue. The recovery of potassium in this process would occur concurrently with the production of alumina.

Brief process description

The feldspar is mined at Mukinbudin and stored in a ROM bin. The mined feldspar is fed from the ROM bin into a tertiary crushing circuit designed to reduce the size of the feldspar to feed the grinding process. The tertiary crushing circuit is fed by an apron feeder and grizzly. The primary crusher is a jaw crusher in open circuit. The product from the jaw crusher and the undersize from the grizzly feed a single deck screen. The oversize from the screen feeds a cone crusher which is also in open circuit. The product from the first cone crusher feeds a second single deck screen from which the oversize reports to the tertiary cone crusher. The tertiary crusher is a cone crusher in closed circuit with the secondary screen. The undersize from the first and secondary screen are combined in a stockpile which feeds grinding.

Due to the small size of the operation the crushing circuit is only operated for 1 month a year, processing excess material and stockpiling it for the grinding process. It is assumed that the Mukinbudin operation will have contract mining and crushing. Following crushing the remainder of the plant has an assumed utilisation of 90 per cent or 7884 operating hours per annum to account for downtime. The mined and crushed ore at Mukinbudin is transported by truck to Kwinana for the remainder of processing.

The grinding circuit consists of a ball mill in closed circuit with an array of hydrocyclones. The hydrocyclone classifies the ground ore to have an overflow at 80 per cent passing (P_{80}) 75 μm. The underflow is recirculated back to the ball mill for further size reduction. The overflow reports to the potassium hydroxide mixing tank where it is mixed with the potassium hydroxide to give a set concentration for the autoclave reactor.

The potassium hydroxide leach autoclave has a solids density of 30 per cent w/w and operates at a temperature of 260°C with a typical residence time of one hr. The slurry from the autoclave feeds a flash vessel which reduces the pressure of the process stream and produces steam which is used to heat the feed to the autoclave. The slurry, now cooled is thickened and filtered to produce a residue with 90 per cent w/w solids and a solution containing sodium hydroxide and potassium hydroxide.

The residue from the potassium hydroxide leach is acid leached using a concentrated sulfuric acid solution. The concentrated sulfuric acid will solubilise any iron, sodium, potassium and aluminium present in the residue. Silica is precipitated from solution leaving a solution rich in sulfates. The slurry from the acid leach is filtered, separating the silica which is neutralised and dried and packaged for sale or disposed of.

The solution from the acid leach enters a solvent extraction circuit where aluminium and iron are separated from the sodium in the feed. The organic containing aluminium and iron is then stripped using a concentrated HCl solution. The concentration of HCl is raised by sparging the solution with HCl gas, precipitating the aluminium chloride from solution as aluminium chloride hydrate (ACH). The impure ACH is centrifuged and redissolved in high purity water before sparging with HCl gas yet again to re-precipitate ACH with higher purity. This is again redissolved and re-precipitated to increase the purity further. The slurry containing the high purity ACH is filtered before feeding a roaster which operates at 700°C converting approximately 75 per cent of the ACH to high purity alumina. The roaster product is then fed to a calciner which operates at 1100°C, converting the remaining ACH to alumina, to give a 99.99 per cent alumina product. The product is then cooled before packaging.

The barren aqueous solution from solvent extraction contains a high concentration of sodium sulfate which can optionally be crystallised using evaporative crystallisation to produce a saleable product. This solution also contains the potassium from the feldspar. If this cannot be selectively precipitated from the solution using an additional evaporative crystalliser then it can be precipitated along with sodium sulfate and potentially separated using flotation provided a sodium sulfate/potassium sulfate double salt does not form. Unlike the lime leaching process and sodium hydroxide leaching process there is unlikely to be a method of producing potassium chloride.

The potassium-bearing alkali solution from the autoclave is reacted with hydrated lime to produce calcium silicate which is then filtered from solution and disposed of. The remaining solution contains predominantly potassium hydroxide with some sodium hydroxide and can be recycled back to the alkali leach autoclave, minimising potassium hydroxide consumption.

The calcium silicate, precipitated silica and excess alkali leach residue are transported to the Mukinbudin site for disposal there. If the potassium sulfate product and sodium sulfate products are not saleable they will be disposed of with the other solid waste products.

Optional – Alternate aluminium extraction process

The proposed process (Figure 5) utilises a sulfuric acid leach to extract aluminium and other elements from the alkali leach residue. If a HCl leach is employed instead, there is potential to produce a potassium chloride product. This would require a low sodium content in the alkali leach residue which may not be realistic due to recycling of the leach solution.

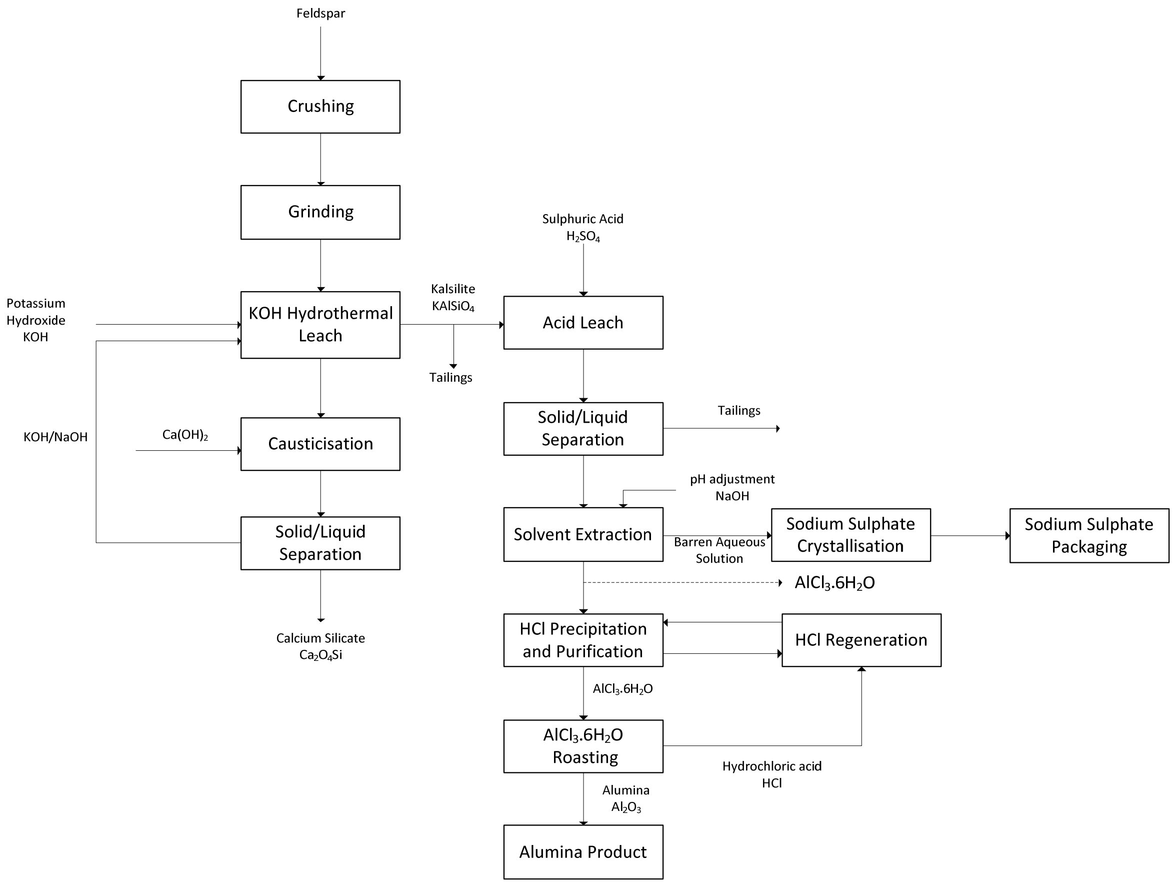


FIG 5 – Block flow diagram for proposed potassium hydroxide process.

ACKNOWLEDGEMENTS

The author would like to thank the AusIMM and METS Engineering Group for permission to publish this paper and all colleagues and engineers at various sites, METS staff and other consultants for their contribution and the management of METS for their permission and constructive criticism of various drafts of this presentation. Thanks also to various vendors for providing technical input.

REFERENCES

Casey, W, Westrich, H and Holdren, G, 1991. Dissolution rates of plagioclase at pH = 2 and 3, *American Mineralogist*, 76:211–217.

Dhawan, N and Agrawal, S, 2022. Recovery of metallic values from feldspar by mechanical and thermal pretreatment followed by acid leaching, *Mining, Metallurgy and Exploration*, 39:1597–1610.

Fujiwara, S, Tamura, Y, Maki, H, Azuma, N and Takeuch, Y, 2007. Development of new high-purity alumina, *Sumitomo Kagaku*, 2007-I:1–7.

Kumanan, M, Sathya, G, Nandakumar, V and Berchmans, L, 2016. Extraction of potash feldspar from K-feldspar mineral by acid and molten salt leaching processes, *IASET*: *International Journal of Metallurgical, Materials and Chemical Engineering, (IASET*:*IJMMCE)*, Special Edition, Jul 2016, pp 1–10.

Mete, K and Huseyin, B, 2019. The correlation of roasting conditions in selective potassium extraction from K-feldspar ore, *Minerals,* 9:109.

Smith, P and Power, G, 2022. High purity alumina – Current and future production, *Mineral Processing and Extractive Metallurgy*, 43(6):747–756.

Türk, T, Üçerler, Z, Burat, F, Bulut, G and Kangal, M, 2021. Extraction of potassium from feldspar by roasting with $CaCl_2$ obtained from acidic leaching of wollastonite calcite ore, *Minerals,* 2021(11):12.

Finding a social license on the deep seabed – risks and mitigation strategies for exploitation activities in the absence of exploitation regulations under UNCLOS

N Eastwood[1], D Whittle[2], I Samsonova[3] and A Murphy[4]

1. Partner, Watson Farley and Williams, Sydney NSW 2000. Email: neastwood@wfw.com
2. Special Counsel, Watson Farley and Williams, Sydney NSW 2000. Email: dwhittle@wfw.com
3. Senior Associate, Watson Farley and Williams, Sydney NSW 2000. Email: isamsonova@wfw.com
4. Associate, Watson Farley and Williams, Bangkok 10330, Thailand. Email: amurphy@wfw.com

EXTENDED ABSTRACT

Part XI of the United Nations Convention on the Law of the Sea (**UNCLOS** or the **Convention**) (United Nations (UN) Division for Ocean Affairs and the Law of the Sea, 1982) establishes a comprehensive regulatory framework for the conduct of deep seabed mining (**DSM**) activities of mineral resources in the **Area** (defined in Article 1(1) of UNCLOS as '*the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction*').

Under that framework, DSM activities can only take place in the Area pursuant to an approved **Plan of Work** in the form of a contract with the International Seabed Authority (ISA) (the **Authority**), a 168-member international body created under UNCLOS to administer the Area. Private contractors can undertake DSM activities if they are sponsored by **Member States** of UNCLOS, providing a dual system of international and domestic regulatory control and oversight for activities in the Area.

The Authority's complete regulatory apparatus is still under construction. Regulations governing prospecting and exploration activities in the Area (the **Exploration Regulations**) were adopted several years ago via a series of decisions from the Authority's Assembly and Council (ISBA/6/A/18 (ISA, 2000); ISBA/19/C/17 (ISA, 2013b); ISBA/19/A/12 (ISA, 2013a), ISBA/20/A/9 (ISA, 2014); ISBA/16/A/12/Rev.1 (ISA, 2010); ISBA/18/A/11 (ISA, 2012)). Several Plans of Work for exploration have been approved under those Regulations. However, the Authority is yet to provisionally adopt or approve the **Exploitation Regulations**, a set of rules governing the commercial recovery of mineral resources from the Area.

Work on the Exploitation Regulations has been underway since 2014, with the complete text of the draft Exploitation Regulations subjected to multiple rounds of stakeholder consultations and expert input from the Authority's Legal and Technical Commission. The Authority is aiming to complete the adoption and approval of the Exploitation Regulations by 2025 (ISBA/28/C/24 (ISA, 2023)).

On 25 June 2021, the small island developing State of the Republic of Nauru (**Nauru**) triggered a provision in Section 1, Paragraph 15(c) of the Annex to the Agreement relating to the Implementation of Part XI (the **1994 Agreement**) (United Nations (UN) General Assembly, 1994) known as the '*two-year rule*'. The two-year rule required the Authority to complete and adopt the Exploitation Regulations within two years from the date of the request.

With the deadline passed, the 1994 Agreement permits prospective contractors to apply for and receive provisional approval of applications for Plans of Work for exploitation – even <u>without the provisional adoption and approval of the Exploitation Regulations</u>. But no such applications have yet been submitted to the Authority. Prospective exploitation contractors are considering the pros and cons in submitting an application for a Plan of Work for exploitation pursuant to their rights contained in the 1994 Agreement or waiting until the Exploitation Regulations are adopted and approved.

This presentation explores the following topics.

First, this presentation examines the applicable criteria and processes for submitting an application for a Plan of Work for exploitation <u>without</u> adopted and approved Exploitation Regulations. It outlines the Authority's likely procedures for analysing such an application. The presentation considers the Authority's obligation to, as Section 1, Paragraph 15(c) of the Annex to the 1994 Agreement instructs, '*consider and provisionally approve*' applications '*based on the provisions of the Convention*' and

various other standards. In doing so, this presentation evaluates the provisional mechanisms offered by UNCLOS and the 1994 Agreement and the ISA's own role. The presentation offers practical instruction on navigating an evolving legal and regulatory landscape for the consideration of an application for a Plan of Work for exploitation in the absence of finalised Exploitation Regulations.

Second, this presentation considers the topic of *social licence* in the DSM context. Social license refers to the level of acceptance or approval that a project receives from stakeholders and communities. The concept originated in the mining industry and holds special relevance for entities seeking to engage in expensive, complex extractive operations. Given the complexities of DSM and its potential environmental and social impacts, obtaining a durable social licence is crucial.

But the scope and character of social license is unsettled. The DSM industry differs significantly from terrestrial mining, deploying highly complex and specialised technology on remote stretches of the seabed far beyond the reach of most human activity. While extensive literature exists on social license theory within the mining industry generally, it is not a perfect fit for DSM. This presentation identifies the scope and extent of social license in the DSM context, identifying possible stakeholders and engagement procedures as well as the potential harms and benefits arising from DSM projects.

Third, this presentation highlights how UNCLOS's existing provisions, oversight mechanisms, and standards already promote social license for the industry, even without the adoption and approval of Exploitation Regulations. These provisions include:

- detailed and specific financial and technical requirements for assessing a Plan of Work under Annex III, including mandatory contractor undertakings to comply with applicable law.
- extensive and actionable environmental protections under Article 145 and Annex III, Article 17(2)(f), including the duty to prevent serious harm to the marine environment in the Area and the obligation to provide detailed programmes for assessing and remedying the impact of DSM activities.
- provisions governing the safety of human life and the preservation of cultural heritage under Articles 146 and 149.
- requirements, under Article 140, that DSM activities benefit humankind as a whole and sufficiently accommodate the rights of impacted parties.
- policy objectives for the Authority under Article 150, including orderly, safe and rational management of Area resources under Article 150.
- relevant norms of customary international law contained in UNCLOS per Article 138.
- the chance for the Authority to provisionally apply certain Exploitation Regulations pending final adoption per Article 162(2)(o)(ii), proving helpful guidance for assessing applications.

This presentation explains how these standards provide robust protections that can help the Authority and prospective contractors secure and maintain a sustainable social license, even without a finalised regulatory code.

Finally, this presentation concludes with recommendations for both the Authority and prospective applicants. For the Authority, it suggests pathways for ensuring the adoption and approval of robust Exploitation Regulations, reducing the regulatory vacuum that currently exists. It also outlines proactive guidance the Authority can provide to its Member States and subsidiary organs, detailing the procedures for assessing applications for Plans of Work for exploitation in the absence of final Exploitation Regulations. It proposes ways for the Authority to reduce regulatory uncertainty in the meantime, including by detailing the role of the Convention's legal regime in securing social license for DSM activities generally.

For prospective contractors, the presentation considers and proposes risk mitigation strategies, outlining the ways the Authority might assess an application for a Plan of Work for exploitation in the absence of adopted and approved Exploitation Regulations. The presentation recommends the preparation of detailed applications with extensive information on environmental risk management, safety procedures, incident responses, community engagement and an array of other factors. The presentation also recommends prospective contractors engage in extensive public outreach, adopting a proactive approach to environmental stewardship and stakeholder engagement to win over public sentiment and strengthen their social license.

In sum, this presentation articulates a comprehensive analysis of the existing regulatory framework for DSM under UNCLOS and the 1994 Agreement, providing key insights into how the Authority and prospective contractors can effectively navigate this landscape. For the Authority, it underscores the requirement to consider and provisionally approve applications for Plans of Work for exploitation submitted to the Authority prior to the adoption and approval of the Exploitation Regulations. For prospective contractors, it explains how to cultivate a durable social license using existing provisions in the Convention and the 1994 Agreement, to secure public legitimacy for a nascent industry.

REFERENCES

International Seabed Authority (ISA), 2000. ISA Assembly: Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area (13 July 2000), ISBA/6/A/18.

International Seabed Authority (ISA), 2010. ISA Assembly: Decision of the Assembly of the International Seabed Authority relating to the regulations on prospecting and exploration for polymetallic sulphides in the Area (15 November 2010) ISBA/16/A/12/Rev.1.

International Seabed Authority (ISA), 2012. ISA Assembly: Decision of the Assembly of the International Seabed Authority relating to the Regulations on Prospecting and Exploration for Cobalt-rich Ferromanganese Crusts in the Area (22 October 2012), ISBA/18/A/11.

International Seabed Authority (ISA), 2013a. ISA Assembly: Decision of the Assembly of the International Seabed Authority concerning overhead charges for the administration and supervision of exploration contracts, 25 July 2013, ISBA/19/A/12.

International Seabed Authority (ISA), 2013b. ISA Council: Decision of the Council of the International Seabed Authority relating to amendments to the Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area and related matters (22 July 2013), ISBA/19/C/17.

International Seabed Authority (ISA), 2014. ISA Assembly: Decision of the Assembly of the International Seabed Authority regarding the amendments to the Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area (24 July 2014), ISBA/20/A/9.

International Seabed Authority (ISA), 2023. ISA Council: Decision of the Council of the International Seabed Authority on a timeline following the expiration of the two-year period pursuant to section 1, paragraph 15, of the annex to the Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea (21 July 2023), ISBA/28/C/24.

United Nations (UN) Division for Ocean Affairs and the Law of the Sea, 1982. United Nations Convention on the Law of the Sea (UNCLOS).

United Nations (UN) General Assembly, 1994. Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982: resolution / adopted by the General Assembly, 48th session, 21 p.

Legacy tailings dams – asset or liability? A case study on sub-aqueous tailings reclamation

M Jones[1]

1. Senior Associate, Enable Advisory, Brisbane Qld 7007.
   Email: marie.jones@enableadvisory.com

ABSTRACT

Legacy tailings storage facilities exist within operating mine sites across Australia. These tailings storage facilities are often viewed as rehabilitation liabilities but with considered assessment may prove to be a resource. Extraction of such a resource might add value to operations by providing cash flow during the development of new mines; providing supplementary mill feed for existing mines undergoing step changes in operations; and supporting mine closure activities.

Hellyer Gold Mines is successfully extracting and reprocessing sub-aqueous material from legacy tailings storage facilities at their Hellyer operation in north-west Tasmania. The Hellyer tailings storage facilities contain poly-metallic material from the Hellyer and Fossey underground deposits dating back to the 1980s as well as material from tailings reprocessing activities by other operators of the Hellyer site. Hellyer Gold Mines is reclaiming sub-aqueous material using cutter-suction dredgers and reprocessing on-site.

Hellyer is the only operation of its type in Australia and few such operations exist worldwide. Key learnings around the estimation of a resource for legacy tailings storage facilities have been acquired at Hellyer that can be applied to the assessment of other tailings storage facilities.

The application of dredging as a mining method at Hellyer is delivered through collaboration with experts from outside the mining industry under the direction of a mining engineer. Key elements required for the planning and delivery of safe and efficient dredging inside tailings storage facilities have been identified at Hellyer and are presented to provide a road map to the development of other dredging operations.

INTRODUCTION

There are over 750 legacy tailings storage facilities on active and inactive mine sites across Australia. Inside these tailings storage facilities are valuable metals which, with advances in minerals processing techniques, it may now be possible to extract. Considered assessment of these tailings storage facilities may unlock new resources on existing mine sites.

Hellyer Gold Mines (HGM) is successfully extracting and reprocessing sub-aqueous material from legacy tailings storage facilities at their Hellyer operation in north-west Tasmania to produce lead and zinc concentrates. The lessons learned from HGM's operations are documented here with a view to informing the development of future mineral resource and ore reserves estimates and the safe extraction of sub-aqueous tailings from other legacy tailings storage facilities.

HISTORY OF HELLYER TAILINGS STORAGE FACILITIES

The Hellyer mine site in the north-west of Tasmania has been active since 1983 as both underground and tailings reprocessing operations (Table 1). The Hellyer site comprises two separate underground voids; Hellyer and Fossey, and six sub-aqueous tailings storage facilities (TSFs) (Figure 1).

TABLE 1
Hellyer operations history.

Year	Entity	Operation type
1983–2000	Aberfoyle Resources Limited Western Metals Resources Limited	Underground (Hellyer Mine)
2006–2008	Polymetals Pty Ltd	Tailings reprocessing
2010–2012	Bass Metals Ltd	Underground (Fossey Mine)
2017–2024	Hellyer Gold Mines Pty Ltd	Tailings reprocessing

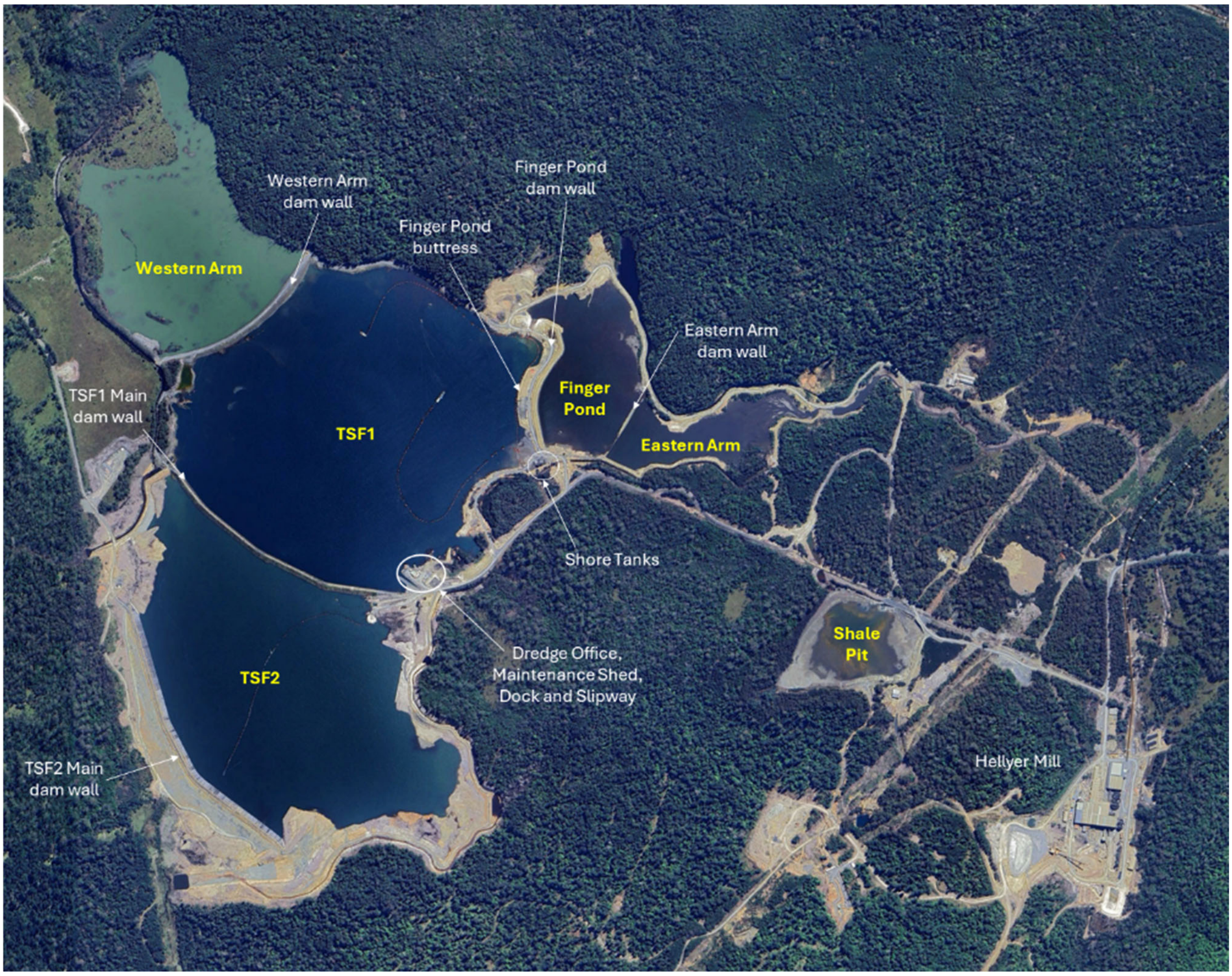


FIG 1 – Hellyer tailings storage facilities, November 2023.

Until the year 2000 all tailings were deposited sub-aqueously into TSF1 which at that time was a single body comprising the current TSF1, the Western Arm, the Fingerpond and the Eastern Arm (Figure 2).

The intermediary embankments: Western Arm Wall, Eastern Arm Wall, Fingerpond Wall and Buttress (Figure 1) were constructed between 2006 to 2008 over unknown quantities of *in situ* tailings. This was done to increase storage capacity without lifting the main TSF1 embankment (TSF1 wall). Consequently, the elevation of the Western Arm, Fingerpond and Eastern Arm TSFs are up to five metres above the waterline of TSF1.

During this period a small open pit (Shale Pit) was repurposed as a TSF to avoid returning tailings to TSF1. TSF2 was constructed during Hellyer Gold Mines' tailings reprocessing operations after capacity in the Western Arm, Fingerpond, Eastern Arm and Shale Pit TSFs was reached.

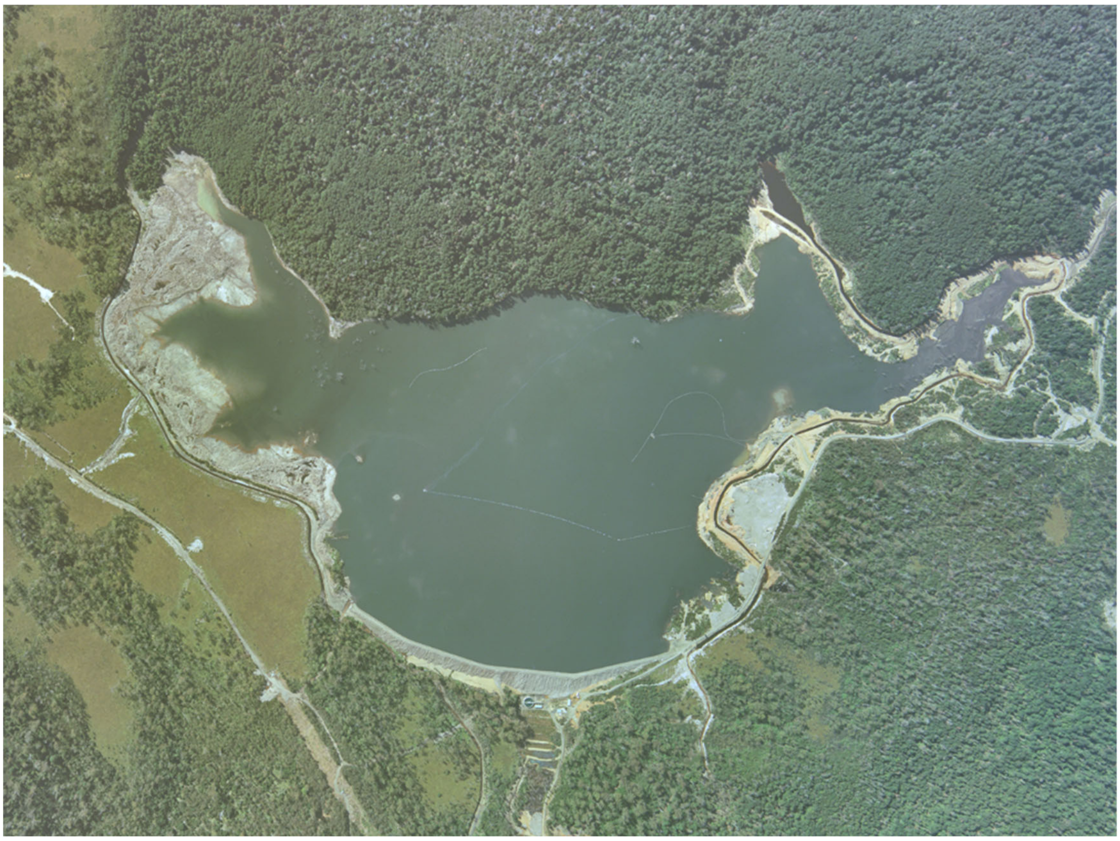


FIG 2 – Hellyer tailings storage facilities, March 1999.

Lessons learned – developing a mineral resource estimate for tailings

Resource boundaries

An accurate understanding of the resource boundaries is important not only for the mineral resource estimate but also for the safety of any future dredging operations. The data required to determine the resource boundaries is:

- an accurate dam floor survey
- as constructed models of dam walls
- Bathymetry surveys (to capture the tailings surface underwater)
- Drone surveys (to capture the tailings surface of any exposed tailings).

For legacy TSFs an accurate dam floor survey and as constructed models of the dam walls can be difficult to obtain. A detailed survey of the area may never have been undertaken; boundaries and depths of any borrow pits within the dam may not have been recorded or surveyed; and the dam floor may not have been cleared prior to commencing tailings deposition. Potential sources of data for legacy tailings dams include physical plans from the operations archives, local surveying firms and the mining regulator.

Bathymetry surveys establish the sub-aqueous surface of the tailings and are undertaken from small craft that can access areas with water depths as shallow as 0.3m. The accuracy of bathymetry surveys is influenced by water turbidity and any tailings deposition activities should cease for a minimum of 12 hrs prior to the survey. Drone surveys can accurately capture the surface of any beached or exposed tailings.

Modelling the in situ tailings

A significant amount of data about the tailings within a legacy TSF is available without any drilling. In addition to the resource boundaries, the data which can assist the development of a mineral resource estimate is the operations historical:

- daily, weekly and monthly processing records, specifically:
  - the feed mineralogy
  - the tail grade and tonnes
  - tailings deposition points.
- process plant design.
- mining production records (ie source orebodies).
- aerial photographs and surveys.

The above data together with the resource boundaries can be used to build spatial models of deposition periods with discreet tailings mineralogy and/or grade to guide the design of drilling programs and modelling constraints.

Broadly, there are two drilling methodologies available for tailings: vibracore and direct push. The selection of drilling methodology influences the quality of the data derived. Both methodologies have been employed in the Hellyer tailings: vibracore in 1998, 2000 and 2017; and direct push in 2021. The advantages and disadvantages of each in relation to sample recovery in the tailings at Hellyer are described in Table 2.

TABLE 2

Tailings drilling methodologies for sample recovery in the Hellyer tailings.

Methodology	Sample recovery	Data derived	Comment
Vibracore	Disturbed	Assay	• Cost-effective • Quick • Maximum depth of sample recovery: 18 m • Water addition required to extract samples from tubes making them unsuitable for *in situ* bulk density determination • Larger samples of representing up to four vertical metres were recovered
Direct Push	Disturbed and Undisturbed	Assay, CPT, *In situ* Bulk Density, PSD	• Expensive • Time consuming (especially at depth) • Maximum depth of sample recovery: 22 m • Undisturbed samples can be recovered suitable for *in situ* bulk density determination

Based on the data derived from the Hellyer drilling programs, a combination of both drilling methodologies is recommended to reduce costs whilst maximising the available data points in legacy TSFs. Important considerations for drilling program design in tailings are the selection of:

- collar point location
- sample size (in vertical metres)
- sample interval
- sample recovery type.

The developed spatial models of deposition periods can be used to guide the selection of collar point location and sample size and interval to ensure that sufficient samples are recovered for each deposition period. The sample recovery type can be guided by the data required: disturbed samples are suitable for assay whereas only undisturbed samples are suitable for the determination of *in situ* bulk density.

The determination of the *in situ* bulk density (IBD) of tailings is challenging. A global calculation from the resource boundaries and historical records of deposited tailings can provide an average IBD. However, testing and reconciliation of the extracted Hellyer tailings indicate a correlation between depth and IBD and tailings grade and IBD. It is recommended that the design of drilling programs in tailings provide for recovery of sufficient undisturbed samples in each deposition period to understand any correlation between depth, tailings grade and IBD.

Drilling program design in tailings should also provide for Vane Shear, Cone Penetration (CPT), particle size distribution (PSD) and geochemistry testing for each deposition period. These tailings material properties are required for the development of an ore reserve estimate: Vane Shear and CPT for the modelling of tailings stability, CPT for dredge anchor selection, PSD for tailings slurry transport calculations and geochemistry to understand the impact of the tailings acidity and water quality on the wear of dredging equipment and infrastructure.

HELLYER DREDGING OPERATIONS

The Hellyer tailings are reclaimed using cutter-suction dredgers (CSDs) and the extracted tailings slurry is pumped via floating pipelines to holding tanks at the waterline of TSF1. The elements that make up the Hellyer dredging operation and their purpose are laid out in Table 3 and Figure 3.

TABLE 3

Hellyer dredging operation elements.

Element	Function
Dredger	Extraction of tailings – See Table 4, Figure 4
Dredge Anchors	Controls the position of the dredger on the TSF and influences the extraction arc (sweep) Dredge anchors are: • located at the TSF waterline, including on TSF embankments (shore anchor) • placed on or in the tailings within the TSF (in-dam anchor)
Anchor Lines	Steel cables that connect the dredger to the dredge anchors
Product Lines	Floating pipelines to transport the extracted tailings slurry from the dredgers to the holding tanks
Trailing Cable	Floated electrical cable supplying power to the dredge pump
Workboat	Support craft with the capacity to: • supply diesel to the dredge pump engine • lift and place in-dam anchors • transport crew and materials to the dredgers • re-locate the dredgers on the TSF
Holding Tanks	Storage of extracted tailings slurry
Support craft	Transport of crew and materials to the dredgers; adjustment and repair of anchor, mooring and product lines; floating infrastructure inspections
Mooring Lines	Controls the position of product lines and the trailing cable on the TSF
Gates	Allows passage of support craft over dredge anchor lines

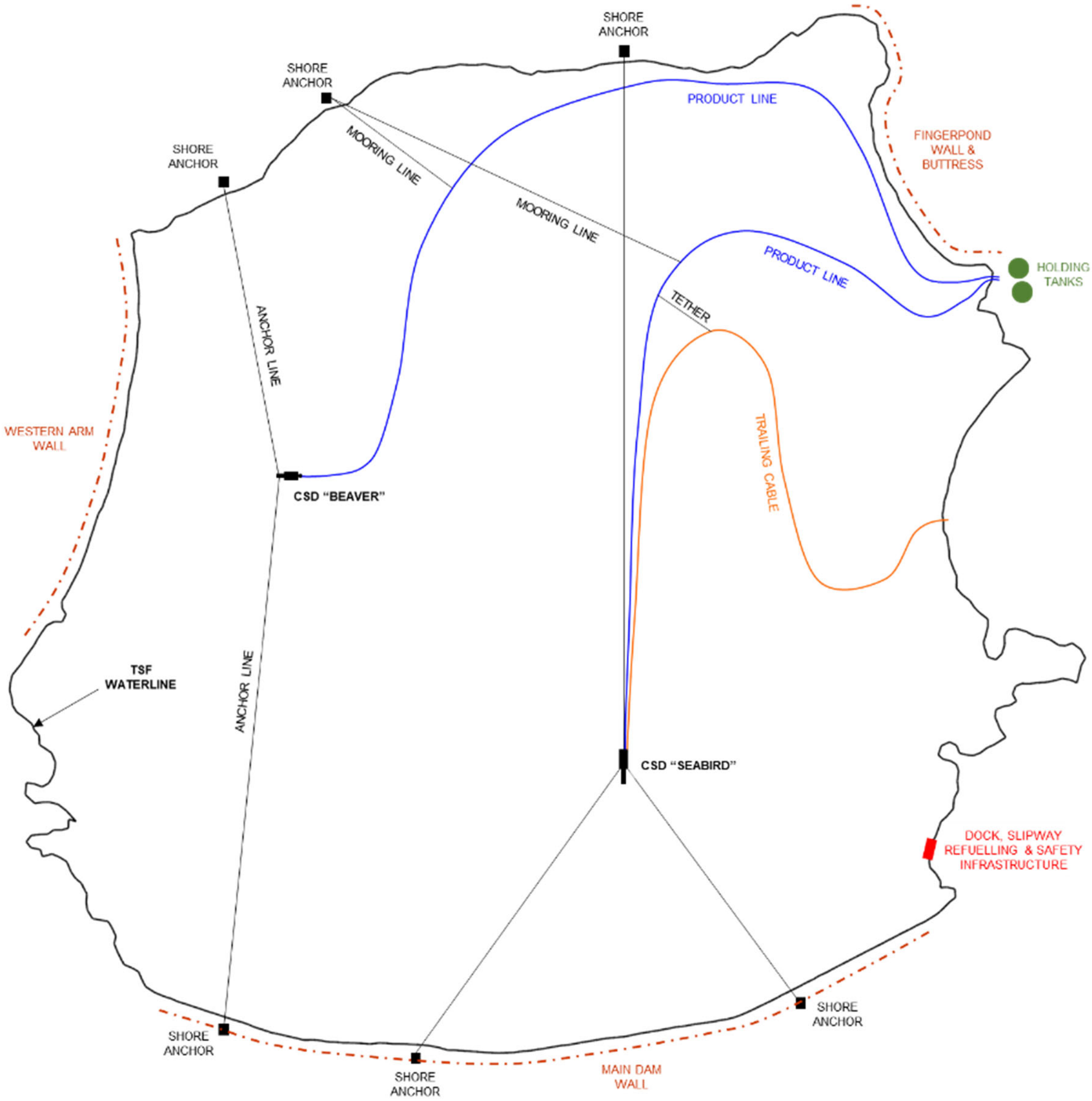


FIG 3 – Indicative Hellyer TSF1 dredging operations layout.

The Hellyer operation has two dredgers with different operating characteristics in service (Table 4, Figure 4). Both are barges without propulsion and anchors and anchor lines are used to control the position of the dredgers on the TSF. Shore anchors are 5 t and 9 t weights located at the waterline around the TSF, including on the TSF embankments. In-dam anchors are 360 kg mushroom type anchors, and the spuds at the stern of the Beaver dredger placed on and in the tailings to be extracted. Relocation of the dredgers and in-dam anchors on the TSF is achieved using the workboat and support craft.

The dredgers breakup the tailings using a rotating cutterhead positioned at the end of a pivoting boom (the ladder) with the dredge suction pump inlet located directly behind the cutterhead. The dredge pump transports the tailings slurry from the cutterhead to the Holding tanks via a floating pipeline.

The dredge operator extracts the tailings by gradually lowering and raising the ladder whilst sweeping the cutterhead from port to starboard. During this process and as the dredge operator moves the dredger forward a face, walls and benches are created. Dredge operators progress the dredger forward until the limit of the anchor lines has been reached. The anchor lines are then adjusted or disconnected and reconnected to allow the workboat and support craft to reposition the dredge at the next location.

TABLE 4

Hellyer dredger operating characteristics.

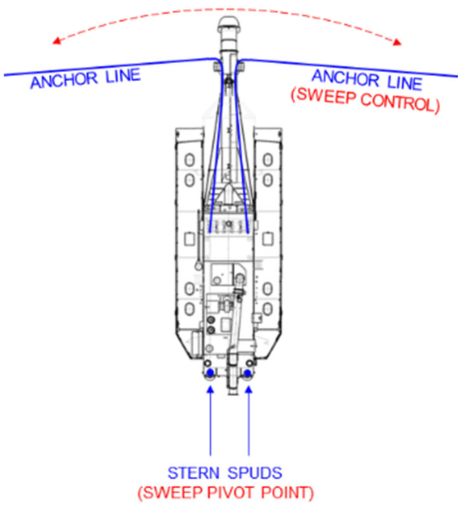
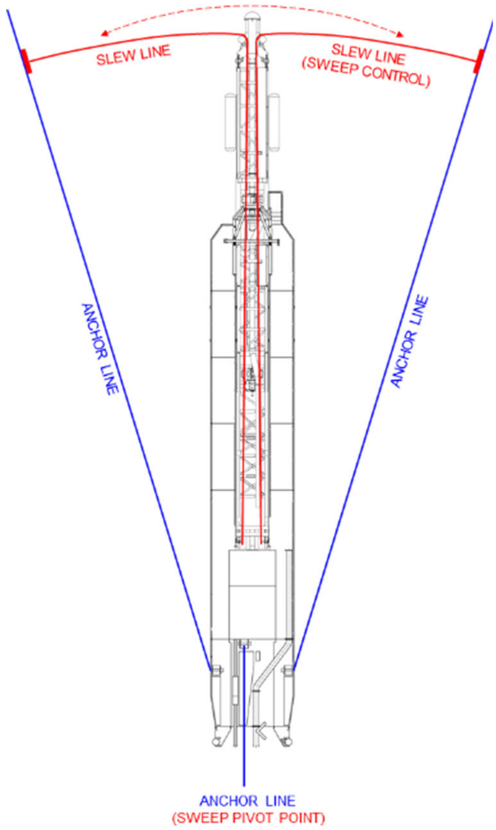
Operating characteristic	CSD 'Beaver'	CSD 'Seabird'
Ladder Type	Fixed Length	Variable with the addition or removal of ladder sections and hull pontoons
Maximum recovery depth	10 m	23 m
Stern Anchor	Spud	Wire line to shore
Port and Starboard Anchors	Wire line to anchor in tailings or wire line to TSF shore	Wire line to TSF shore
Dredge Operation	Ladder sweep pivots from stern spud and is controlled by winches on port and starboard anchor lines. Forward movement controlled by the raising and lowering of stern spuds. Reverse movement not possible unassisted	Ladder sweep controlled by port and starboard winches on slew ropes passing through blocks located in the port and starboard anchor lines. Forward and reverse movement controlled by winches on stern, port and starboard anchor lines
Dredge Sweep Schematic		

FIG 4 – CSD 'Seabird' and CSD 'Beaver'.

The principal hazards of dredging operations are water, weather conditions, floating infrastructure, and tailings stability.

Dredging operations require personnel to work on water and some tasks require dredge operators to work over the side of support craft. Weather conditions such as high winds, low temperatures, and low visibility due to fog, rain and darkness impact the ability to safely carry out work on water. Anchor lines, mooring lines, product lines and the trailing cable impact the ability to safely transit support craft over the TSF, particularly in low visibility conditions. Once disturbed the tailings within the TSF are highly mobile and movement of large volumes of tailings can trigger waves that impact the position and stability of the dredgers on the TSF.

Lessons learned – developing an ore reserve estimate for tailings

Addressing tailings stability

The critical parameters for addressing the principal hazard of tailings stability in the development of an ore reserve estimate are:

- maximum tailings bench height
- maximum tailings face angles
- minimum tailings berm width such that tailings benches behave as discreet entities
- extraction exclusion zones for TSF embankment stability.

Numerical modelling using the tailings material properties drawn from Vane Shear and CPT testing during resource development determines these parameters. Bench height, berm width, face angles and exclusion zone boundaries guide the development of a safe extraction schedule.

Determination of achievable production rates

The maximum throughput rate of the processing plant (at average resource grade) sets the lower limit for the dredger production rate. This allows for shift change, planned and unplanned dredger maintenance activities. The following parameters guide dredge pump selection:

- the relative RL differential between the TSF maximum depth and the holding tank inlet
- product line length required to access the entire surface area of the TSF
- product line diameter
- tailings material properties.

The specifications of the selected dredge pump are a required input into the dredge asset selection process. The pump curve of the selected dredge pump dictates the maximum achievable production rates from different tailings benches (differentiated by distance below the TSF waterline). These production rates guide the development of an achievable extraction schedule.

Selection of appropriate anchoring methodology

Dredge anchors are used to control the position of the dredgers on the TSF and influence the extraction sweep. The characteristics of the TSF that influence the selection of anchoring methodology are:

- the accessibility of the waterline around the perimeter of the TSF
- tailings material properties
- the depth of water cover over the TSF
- the size of TSF floor area.

Shore anchors are positioned at the water line and access is required for anchor installation and relocation, the connection of anchor lines and anchor inspections. Ideally this requires a perimeter access road that can provide for two-way traffic. Placement of shore anchors on embankment wall crests that provide for one-way traffic only is possible where anchors can be installed below the crest in the downstream embankment wall.

A water cover of less than 1.5 m over the tailings prohibits the use of in-dam anchors. Workboat access to the port and starboard in-dam anchor locations is required and workboats capable of lifting in-dam anchors generally have a minimum draft of 1.5 m. Dredgers with a stern spud as an in-dam anchor also have a minimum draft of 1.5 m.

The material properties of the *in situ* tailings determine the expected penetration of spud and other in-dam anchors. In-dam anchors are unsuitable where the expected spud and anchor penetration exceeds the capacity of the dredger spud and workboat anchor raising systems.

Observations from Hellyer operations show recovery of tailings from the TSF floor to be greater when a shore stern anchor is utilised. In this configuration the dredge operator controls the reverse movement of the dredger via winches. This facilitates manoeuvrability around hazards such as rocks, tree stumps and fallen trees on the dam floor resulting in greater tailings recovery. Reverse movement of dredgers with a stern spud (such as the Beaver dredger) is not possible without assistance from the Workboat and support craft.

The selected anchor methodology is required as an input into the dredge asset selection process.

Selection of appropriate dredging asset

The selection of the appropriate dredging asset is influenced by the following parameters:

- dredge pump specifications
- anchor methodology
- power availability

- maximum depth of the TSF (distance between the waterline and the TSF floor).

Electric dredgers have comparatively lower operating costs but require substantial electrical infrastructure and a floated trailing cable of sufficient length to facilitate access across the TSF. Losses across the trailing cable limits the maximum operational area of an electric dredger. Diesel dredgers have comparatively higher operating costs and require shore based refuelling infrastructure and watercraft (generally a Workboat). Over a TSF with a large surface area a diesel dredger provides greater flexibility.

The maximum depth of the TSF determines the required ladder length. Where this is greater than the ladder lengths of available dredgers two options are possible:

- a custom modular dredger where the ladder length can be increased and decreased with the addition and removal of ladder sections and hull pontoons (such as Hellyer operations' Seabird dredger).
- staged extraction where after the removal of an upper layer of tailings across the TSF, the water level of the TSF is lowered to facilitate access to tailings beyond the reach of the ladder of available dredgers.

The selected dredge asset(s) guide the cost estimation process for the development of an ore reserve estimate.

Ancillary selection

Ancillary equipment and infrastructure required to support safe dredging operations are:

- Support craft
- Workboat
- Product line
- Holding Tanks
- Slipway and dock
- Electrical infrastructure
- Diesel storage and refuelling infrastructure
- Safety equipment and infrastructure.

Considerations for the selection of support craft include propulsion and steering type, fuel type, hull material and size. Diesel outboard propulsion with central steering control is recommended. Hull material is guided by the TSF water quality. Support craft size is guided by manoeuvrability on water, number of crew to be carried and the ease of trailering/launching for maintenance.

Workboat selection is guided by anchor methodology, product line diameter and dredger diesel consumption, the aim being to refuel a diesel dredger over water in daylight hours only.

Consideration of tailings material properties is required to ensure that tailings remain in suspension throughout the product line from the dredge pump to the holding tank inlet. Buildup of settled tailings in the product line causes product line blockages that are difficult to safely repair on water. Larger diameter product lines reduce friction losses but increase the potential for tailings settlement and are subject to greater wind action on the TSF.

Holding tanks at the TSF shoreline are required to manage dredge pump pressures and provide surge capacity to facilitate planned maintenance activities. Holding tank size is guided by the production rate with a minimum of 12 hrs capacity recommended.

A slipway in which to conduct dry-dock maintenance of dredgers, workboat and support craft is required. Slipway size and length is defined by the selected dredge asset. A dock is required to safely load and unload personnel and materials from the support craft and workboat.

The slipway, dock and refuelling and safety infrastructure all require lighting and power. Safety infrastructure for dredging operations includes communications, a heated drying room and first aid room. The selected ancillary equipment and infrastructure guide the cost estimation process for the development of an ore reserve estimate.

Lessons learned – managing dredging operations

Hellyer dredging operations has safely managed simultaneous dredging by two dredgers and associated ancillary infrastructure on tailings storage facility of which two of the three embankment walls are constructed on top of an unknown quantity of tailings. Key learnings regarding managing regulatory compliance as well as the principal hazards of water, weather conditions, floating infrastructure and tailings stability have been drawn from this operating experience.

Regulatory compliance

Commercial operations conducted from vessels falls under the purview of the Australian Maritime Safety Authority (AMSA). The legislation under which AMSA operates is highly prescriptive and covers certification and compliance of vessels, safety management systems for marine operations, and vessel operator certification and training requirements. To assist with understanding compliance obligations, it is recommended that a prospective dredging operation establish relationships with:

- An AMSA accredited marine surveyor (vessel certification and compliance).
- A marine operations specialist (safety management system, safe operating procedures and emergency response training).
- A maritime industry training provider (vessel operator certification and training).

Water and weather conditions

Robust risk assessments are required to determine what tasks can safely be performed on water and the weather conditions in which those tasks can occur. Engagement with a marine operations specialist will ensure that all risks associated with conducting work over water have been identified and addressed in the safety management system.

The development of trigger action response plans (TARPS) for weather conditions such as high winds, low temperatures, low visibility (due to rain and fog) and electrical storms is recommended to guide the daily execution of the production plan.

Floating infrastructure

Infrastructure located on and in the TSF presents a hazard to both the anchored dredgers and the traverse of support craft over the TSF. Wind action on floated product lines and trailing cables can move their position on the TSF such that it interferes with the dredger anchor lines and extraction arc (sweep). Modelling by marine operations specialists is required to determine the placement and type of mooring lines to prevent movement of product lines. Tethers are utilised to protect a trailing cable from damage.

Anchor lines, mooring lines and tethers are rope or steel cables that lie just under the water surface of the TSF. Support craft traversing over the TSF can become snagged on these lines causing injury to personnel and damage to the support craft. Visibility can be improved through the installation of buoys and reflective markers on the lines and tethers. Sections of the anchor and mooring lines can be weighted to increase the distance of the line below the water to form a gate over which support craft can safely pass.

Tailings stability

Numerical modelling to define the maximum bench height, minimum berm width, face angle and exclusion zones from TSF embankments guides the development of a safe extraction schedule.

During dredging operations, regular bathymetry surveys are required to monitor tailings stability and manage compliance to the extraction schedule. Monthly surveys are recommended to:

- identify non-compliant zones to address as soon as practicable in production planning.
- facilitate production reporting and reconciliation.

The accuracy of bathymetry surveys is influenced by water turbidity and any dredging activities should cease for a minimum of 12 hrs prior to the survey. Bathymetry surveys are a specialist service not normally within the scope of mining and cadastral surveyors.

Water turbidity resulting from dredging activities prohibits any real-time monitoring of face angles however real-time visualisation of benches and face angles based on the movement of the cutterhead is provided by dredge management software such as DredgePack to the dredge operator.

CONCLUSION

Legacy tailings storage facilities contain valuable metals which, with advances in minerals processing techniques, it may now be possible to extract. Understanding the potential value within these tailings storage facilities requires the development of mineral resource and ore reserve estimates. This paper provides a roadmap for the development of a mineral resource and ore reserve estimates for legacy tailings dams. The principal hazards associated with dredging operations are identified and steps to address those principal hazards during the development of an ore reserve estimate and in the management of dredging operations are defined.

ACKNOWLEDGEMENTS

I gratefully acknowledge *Hellyer Gold Mines* for the continuing opportunity to support the Dredge Crew and the dredging operation and for permission to publish the lessons learned through the provision of this support in this paper.

I thank *Sub41* for their invaluable marine operations experience and willingness to apply this in support of the Dredge Crew and the Hellyer operation as a whole.

Applicability of TBM (tunnel boring machine) for deep lunar subsurface exploration

T Y Ko[1], J H Hwang[2], S J Park[2] and Y S Kang[2]

1. Assistant Professor, Kangwon National University, Chuncheon 24341, Korea.
   Email: tyko@kangwon.ac.kr
2. Graduate Student, Kangwon National University, Chuncheon 24341, Korea.

ABSTRACT

The lunar subsurface, particularly the lava tubes formed by ancient volcanic activity, presents a promising environment for establishing safe and sustainable human habitats on the Moon. Tunnel Boring Machines (TBMs), widely used for excavating tunnels on Earth, offer a potential solution for developing these subsurface spaces. However, the unique lunar conditions, including extreme temperatures, high vacuum, radiation, and the extraordinary strength and abrasiveness of lunar rocks, necessitate significant adaptations to existing TBM technology. This study investigates the feasibility of utilising TBMs for lunar subsurface exploration and base construction, addressing the challenges posed by the harsh lunar environment. We review previous conceptual designs for lunar TBMs, highlighting their strengths and limitations in addressing these challenges. Additionally, we explore innovative excavation methods, such as microwave-assisted rock weakening and undercutting techniques, to enhance the efficiency and effectiveness of lunar TBM operations. By evaluating the geological characteristics of the lunar crust and analysing the potential of lava tubes as launching points for TBM operations, this study provides a comprehensive assessment of the technical requirements and operational considerations for lunar TBM implementation. The findings of this research contribute to the growing body of knowledge on lunar base development and pave the way for future human exploration and utilisation of the Moon's subsurface resources.

INTRODUCTION

The lunar environment, with its extreme temperatures, high vacuum, radiation, lunar dust, and micrometeorite impacts, presents a formidable challenge for human exploration and the establishment of permanent lunar bases. While the lunar surface is rich in resources and scientific interest, it is a hostile environment for long-term habitation. These conditions necessitate the development of protective habitats that can shield humans from the harsh lunar environment.

In this regard, the lunar subsurface has emerged as a promising solution. Lava tubes, formed by ancient volcanic activity, offer natural shelters within the lunar crust. These subterranean cavities provide a stable thermal environment, protection from radiation, and a barrier against micrometeorite impacts. The potential of lava tubes as sites for lunar bases has been recognised for decades, and their natural openings could serve as ideal locations for launching Tunnel Boring Machines (TBMs) to further expand and develop these subsurface habitats.

Tunnel Boring Machines (TBMs), a technology widely used on Earth for excavating tunnels, offer a potential solution for developing lunar subsurface habitats. TBMs have the capability to excavate large volumes of material efficiently and create stable tunnels in various geological conditions. However, the unique environment of the moon, including the high strength and abrasiveness of lunar rock, necessitates significant adaptations to TBM technology and operational procedures.

This study aims to explore in-depth the feasibility of using TBMs for lunar subsurface exploration and base construction, with a particular focus on utilising lava tubes as launching points for TBM operations. We will examine the environmental and geological characteristics of the moon that pose challenges and opportunities for TBM operations, including the development of innovative excavation methods to overcome the high strength of lunar rock. This includes investigating the potential of utilising microwave technology to pre-weaken the rock and reduce excavation energy requirements, as well as implementing undercutting techniques to induce tensile failure in the rock mass, thereby facilitating TBM advancement. We will review previous research and proposals for lunar TBMs and identify the key technical requirements for adapting this technology to the lunar environment. By addressing the challenges and opportunities associated with lunar TBM operations, this study seeks to contribute to the growing body of knowledge on lunar base development and pave the way for future human exploration and utilisation of the moon's subsurface resources.

LUNAR ENVIRONMENTAL AND GEOLOGICAL CONSIDERATIONS

The lunar environment and geological characteristics present unique challenges and opportunities for the application of Tunnel Boring Machines (TBMs) in subsurface exploration and base construction.

Lunar environment

The extreme environmental conditions on the moon, including the extreme temperature variations, vacuum, radiation, and micro-meteorite impacts, pose significant challenges for TBM operations. The temperature on the lunar surface can fluctuate between -173°C during the lunar night and 127°C during the lunar day. These extreme temperatures can affect the performance of TBM components, such as lubricants, seals, and electronic systems. The vacuum environment on the moon can lead to outgassing of volatile materials from the TBM and the surrounding rock, potentially causing contamination and operational issues. The lack of atmosphere also eliminates the possibility of using conventional cooling methods for the TBM, requiring alternative thermal management solutions. Micro-meteorite impacts, although small in size, can cause damage to the TBM's external components and sensors, requiring robust design and protective measures. Launching TBMs from within lava tubes can provide a natural shield against these environmental hazards, making it a more feasible and sustainable approach for lunar subsurface development.

Lunar geology

The lunar surface is covered by a layer of loose, unconsolidated material known as regolith. This regolith is formed by the continuous bombardment of micrometeorites, radiation weathering, and thermal cycling. The composition of lunar regolith varies depending on location, but it generally consists of rock fragments, mineral grains, and glass beads. While the regolith layer itself is not the primary target for TBM excavation in this context, its presence and properties need to be considered when launching TBMs from the surface. The regolith's low cohesion and abrasive nature can pose challenges for TBM launch and initial excavation phases.

Beneath the regolith lies the lunar crust, which is the primary target for TBM excavation and subsequent subsurface development. The lunar crust is composed primarily of igneous rocks such as basalt and anorthosite. The crustal thickness varies across the moon, ranging from approximately 60 km on the near side to over 100 km on the far side. The lunar crust is believed to be relatively homogeneous in composition, with variations primarily related to the abundance of different minerals and the degree of impact cratering.

As illustrated in Figure 1, the lunar crust can be broadly divided into several layers based on its geological characteristics and the degree of fracturing resulting from impact events. The uppermost layer, consisting of regolith and large-scale ejecta, is characterised by its loose and unconsolidated nature. Beneath this lies the structurally disturbed crust, which is heavily fractured and fragmented due to the impact of large meteoroids. The fractured crust, located at greater depths, exhibits a decreasing density of fractures as the *in situ* rock becomes more intact. Finally, the deepest layer represents the intact lunar crust, which is relatively undisturbed and exhibits the highest strength and integrity.

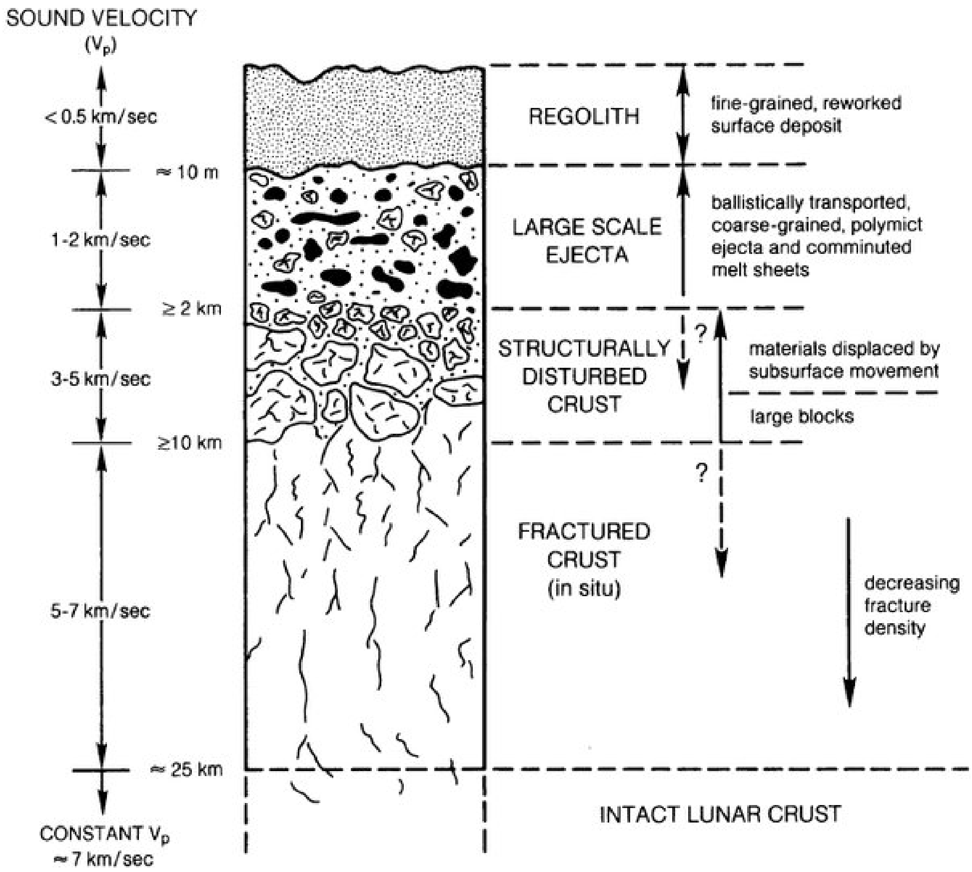


FIG 1 – The vertical structure of the lunar regolith and crust (Carroll, 2010).

The geological formations within the lunar crust, including lava tubes, and mare basalt, play a crucial role in determining the feasibility and safety of TBM operations. Lava tubes, formed by ancient volcanic activity, are of particular interest as potential sites for lunar bases due to their natural shielding properties and potential as launching points for TBM operations. However, the size, shape, and stability of lava tubes can vary significantly, requiring careful assessment before TBM deployment. The existence of large and stable lava tubes on Earth, such as the Manjanggul Lava Tube in Jeju Island, South Korea, suggests that similar formations on the moon could also provide ample space and structural integrity for subsurface habitats and TBM operations.

While direct strength tests on lunar rock samples obtained from the Apollo missions are limited, indirect evidence from density and P-wave velocity measurements suggests that lunar rock, particularly in the deep subsurface, may exhibit high uniaxial compressive strength (UCS) (Table 1). This is due to a combination of factors, including rapid magma cooling, lack of weathering processes, compression and recrystallisation from meteorite impacts, and thermal hardening effects.

TABLE 1

Density and P-wave velocity of lunar and terrestrial rocks (Warren *et al*, 1973; Bell, 2007).

Rock type	Density (g/cm^3)	P-wave velocity (km/s)	UCS (MPa)
Lunar basalt	3.2	6.9–7.4	-
Lunar anorthosite	2.6–3.0	5.8–7.3	-
Terrestrial basalt	2.6–2.8	5.2–6.4	75–250

REVIEW OF PREVIOUS LUNAR TBM CONCEPTS

Prior research has explored the concept of utilising Tunnel Boring Machines (TBMs) for lunar subsurface development, recognising the potential benefits of such an approach in establishing safe and habitable environments for lunar bases. Two notable studies have investigated the feasibility and design considerations for lunar TBMs, offering valuable insights into the challenges and opportunities associated with this technology.

In 1988, Allen *et al* (1988) proposed a conceptual design for a Lunar Tunneler, a fully automated TBM designed to excavate lunar material and simultaneously create a rigid, glass-like ceramic lining to support the tunnel walls. The proposed design incorporated a rotating mechanical head with disc cutters for excavation, a hydraulic gripper propulsion system, and a laser communication and computer system for guidance and control. The study also explored the use of a nuclear reactor for power generation and a heat exchange system for utilising the excavated lunar material to create the ceramic lining. While this study provided a comprehensive overview of the technical requirements and design considerations for a lunar TBM, it was limited by the technology available at the time and the lack of detailed knowledge about the lunar subsurface environment.

More recently, Rostami, Dreyer and Blair (2018) revisited the concept of lunar TBMs, focusing on the challenges and opportunities presented by new discoveries about the moon, such as the presence of lava tubes and water ice in permanently shadowed regions. The study emphasised the adaptability of TBMs to various geological conditions and their potential for accessing and developing these unique lunar environments. The authors highlighted the need for modifications to existing TBM designs to address the specific challenges of the lunar environment, such as the extreme temperatures, vacuum, and abrasive nature of lunar regolith. They also discussed the potential for utilising lunar resources, such as basalt and regolith, in the construction and operation of lunar TBMs.

Both studies emphasise the potential of TBMs as a valuable tool for lunar subsurface exploration and development. They highlight the need for further research and development to address the technical challenges and optimise TBM designs for the lunar environment. The utilisation of lava tubes as launching points for TBMs and the potential for *in situ* resource utilisation are promising avenues for future research and development in this field.

INNOVATIVE EXCAVATION METHODS FOR LUNAR TBM

The high strength and abrasiveness of lunar rock present significant challenges for TBM excavation, as discussed in the previous section. To address these challenges and improve the efficiency and effectiveness of lunar TBM operations, innovative excavation methods need to be explored. This chapter will focus on two promising techniques: microwave-assisted rock weakening and undercutting.

Microwave-assisted rock weakening

Microwave technology has shown potential in pre-weakening rock by inducing thermal stresses and microfractures, thereby reducing its strength and facilitating excavation. Microwaves can penetrate the rock surface and selectively heat minerals with high dielectric loss, such as feldspar and mica. This differential heating creates thermal stresses that can lead to the formation of microfractures, weakening the rock mass and making it easier to excavate.

To investigate the potential of microwave pre-treatment for lunar excavation, we conducted a series of experiments on basalt samples, a common rock type found on the lunar surface. The samples were exposed to 1000 W of microwave radiation for 3 mins. The results showed a significant decrease in both P-wave velocity and Leeb rebound hardness, indicating a reduction in the rock's strength and an increase in its drillability.

The application of microwave technology to lunar TBM excavation offers several potential benefits. By pre-weakening the rock, it can reduce the cutting forces required for excavation, leading to lower energy consumption and reduced wear on the TBM's cutting tools. Additionally, microwave pre-treatment can induce controlled fracturing in the rock, potentially improving the fragmentation process and facilitating the removal of excavated material.

However, the implementation of microwave technology in the lunar environment also presents challenges. The vacuum environment can affect the propagation and absorption of microwaves, requiring adjustments to the design and operation of the microwave system. The extreme temperatures on the moon can also pose challenges for the thermal management of the microwave system and the surrounding rock.

Undercutting

Undercutting is a technique used to facilitate the excavation process by inducing tensile failure in the rock mass ahead of the TBM's cutting head. This is achieved by creating a void or an undercut beneath the rock face, allowing the overlying rock to break off under its own weight or with minimal additional force.

The undercutting process typically involves the use of specialised undercutting tools attached to the TBM's cutting head. These tools grind away a portion of the rock face, creating a horizontal or angled undercut. As the undercut progresses, the rock above the void becomes unsupported and eventually fractures due to its self-weight and the tensile stresses induced by the undercutting.

Undercutting can significantly reduce the energy consumption and wear on the TBM's cutting tools compared to direct full-face excavation of hard and abrasive rock. By inducing tensile failure, the rock can be broken more efficiently, reducing the need for extensive mechanical cutting and grinding.

On the lunar surface, the application of undercutting techniques could be particularly beneficial due to the high strength and abrasiveness of lunar rocks, as mentioned earlier. The lack of weathering processes and the intense thermal and impact hardening have likely contributed to the formation of exceptionally strong and dense lunar rocks, making them challenging to excavate using conventional TBM cutting methods.

By employing undercutting techniques, lunar TBMs could potentially reduce the energy requirements for excavation and mitigate the wear on cutting tools. The low gravity environment on the Moon could also facilitate the fracturing and dislodging of the rock above the undercut, as the self-weight of the rock would be lower compared to Earth conditions.

However, it is important to note that the effectiveness of undercutting on the Moon may depend on the specific geological characteristics of the lunar rock formations being excavated. Additionally, the implementation of undercutting techniques may require modifications to the TBM design and operational procedures to adapt to the unique lunar environment.

CONCLUSIONS

This study has explored the feasibility of using Tunnel Boring Machines (TBMs) for lunar subsurface exploration and base construction. The unique challenges posed by the lunar environment, such as extreme temperatures, vacuum, radiation, and the high strength of lunar rock, necessitate significant adaptations to TBM technology and operational procedures. However, the potential benefits of utilising the lunar subsurface for establishing safe and habitable environments for human presence on the moon make it a compelling endeavour.

Lava tubes, with their natural shielding properties and potential as launching points for TBMs, offer a promising avenue for lunar base development. The existence of large and stable lava tubes on Earth suggests that similar formations on the moon could provide ample space and structural integrity for subsurface habitats.

Innovative excavation methods, such as microwave-assisted rock weakening and undercutting, have shown promise in mitigating the challenges posed by the high strength of lunar rock. These techniques can potentially reduce excavation energy requirements, minimise wear and tear on TBM cutting tools, and improve the overall efficiency and safety of lunar TBM operations.

While this study has highlighted the potential of TBMs for lunar subsurface development, further research and development are needed to address the technical challenges and optimise TBM designs for the lunar environment. The development of lunar-capable TBMs requires a multidisciplinary approach, involving collaboration between engineers, scientists, and space agencies.

ACKNOWLEDGEMENTS

Research for this paper was carried out under the KICT Research Program (project no. 20240184–001, Development of environmental simulator and advanced construction technologies over TRL6 in extreme conditions) funded by the Ministry of Science and ICT.

REFERENCES

Allen, C S, Cooper, D W, Davila Jr, D, Mahendra, C S and Tagaras, M A, 1988. Proposal for a lunar tunnel-boring machine, NASA contractor report.

Bell, F G, 2007. *Engineering Geology*, 581 p (Elsevier Science).

Carroll, K A, 2010. Gravity Gradiometry for Lunar Surface Exploration, in Proceedings 15th CASI Canadian Astronautics Conference.

Rostami, J, Dreyer, C and Blair, B, 2018. Lunar Tunnel Boring Machines, in *Proceedings Earth and Space 2018,* pp 240–252 (American Society of Civil Engineers: Cleveland).

Warren, N, Trice, R, Soga, N and Anderson, O L, 1973. Rock physics properties of some lunar samples, in *Proceedings the Fourth Lunar Science Conference,* pp 2611–2629 (Lunar Science Institute: Houston).

Space mining – managing astronomical complexity

K Markovic[1], D Brown[2] and Z Tabor[3]

1. Systems Engineer, Nova Systems, Southbank Vic 3006.
   Email: kristina.markovic@novasystems.com
2. Systems Engineer, Nova Systems, Fremantle WA 6160.
   Email: daniel.brown@novasystems.com
3. Systems Engineer, Nova Systems, Fremantle WA 6160.
   Email: zachary.tabor@novasystem.com

ABSTRACT

From ancient times to the modern world, the mining industry has played a pivotal role in shaping the society that we live in today. It remains an integral part of everyday life and is a catalyst for both technological and economic growth. With finite resources on Earth, and growing pressures surrounding climate change and the environment, space mining opportunities have become of increasing interest. Recent discoveries have shown celestial bodies including the Moon and surrounding asteroids, contain an abundance of critical minerals, as well as resources necessary to sustain human life. These discoveries coupled with a transition into the digital and autonomous age, offer an innovative solution to solving some of the mining challenges currently being faced on Earth. Similarly, they also offer a pathway to enabling deep space exploration and off Earth exploratory missions. However, like with mining operations on Earth, space remains and immensely challenging and complex operational environment. The inhospitable nature of space poses new challenges, including communication barriers, lunar dust, cosmic radiation, and gravity. The challenges and risks are not just technological, as Environmental, Social, and Governance (ESG) factors must also be considered to prevent unintended consequences and hazards. Furthermore, future workforce, law, financial, and security systems must evolve to enable space mining to take place. These are all known aspects to begin with, but as the complexity of the space grows it becomes apparent that a holistic approach to assess and manage these factors will be required.

Systems engineering is a multi-disciplinary approach that incorporates engineering management to design, integrate and sustain complex systems. Its application in space mining will be vital to ensure all systems, factors, and constraints are defined. Through a system-of-systems method the interfaces and connections between all the factors can be established to ensure safe and effective practices are sustained across the industry, with all risks appropriately managed. This paper aims to explore the key challenges, barriers, and interfaces that underpin the feasibility of the space mining industry. Furthermore, it seeks to discuss how systems engineering principles can be applied to overcome some of these challenges, and in doing so help create a sustainable and operational industry for the future of humankind.

INTRODUCTION

The space mining revolution, once considered a fictional concept, is quickly gaining interest and momentum across the globe. Composition tests have shown that the moon and asteroids contain an abundance of critical minerals. In some cases, these celestial bodies have been found to be so rich in platinum group metals, that the quantity available would outweigh the amount of platinum group metals that have ever been mined on Earth (Atkinson, 2015). As reserves on Earth continue to deplete, and with the growing pressures of climate change, the abundance of critical minerals in space presents an opportunity to alleviate some of these concerns. The space resources of interest extend beyond critical and platinum group minerals, with helium and ice deposits that can be decomposed into hydrogen and oxygen, opening opportunities to solve key challenges surrounding deep space exploration. For example, performance of propulsion systems is an ongoing limitation for spacecraft to travel further into space, primarily due to the set amount of fuel available once a spacecraft leaves Earth. Moreover, oxygen and water remain critical resources for human life. With the option to access these resources off-Earth, a pathway of possibilities opens for space exploration.

However, despite the opportunities that space mining presents, opening the gateway to space mining is not an easy endeavour. The technological solution for space mining is fraught with challenges due to the harsh and extreme nature of the environment and are amplified by the remoteness and extensive distances that need to be overcome to access and transport space resources. Furthermore, space mining challenges are not limited to technology, as the solutions to the economic and ethical factors remain unclear.

As further challenges arise and the complexity of the space grows, managing and balancing these factors impacts the feasibility of space mining operations. This paper explores the key elements that need to be considered for space mining to eventuate. It also discusses how systems engineering can be utilised to manage these complex factors, reduce risks across missions and operations, and ensure a sustainable future for the industry.

TECHNOLOGY

What is the technological solution?

Technology is continuing to develop at a rapid pace and shape the world around us. In the mining industry, we are seeing a transition towards automation and digitisation. These advancements and innovations are demonstrating improvements in both safety and efficiency across operations. Similar trends can be seen in the space industry, with artificial intelligence and data analytics allowing for more frequent and challenging missions to space. Even though these trends are continuing to evolve, a technological solution for space mining operations currently does not exist.

The mining industry is acquainted with operating in inhospitable and harsh environments due to the extreme locations of commodity reserves. However, mining outside of Earth presents additional challenges that need to be addressed. To name a few factors, the technology needs to be fit to overcome lunar dust, micro gravity, cosmic radiation, and permanent darkness. Once in space, the technology can't be accessed as readily as it can on Earth, increasing the consequences of mission risks, failures, and errors. In addition, the technology needs to overcome current costs associated with space travel and autonomous operations.

To determine what the best technological solution for space mining might look like, the first aspect will therefore be to understand the context and environment in which space mining will take place in. The second will be to understand the space mining life cycle and determine what needs to be achieved from space mining. The technology to send objects to space, collect asteroid samples, and deliver them back to Earth is available and has proven to be successful through programs such as the NASA OSIRIS-Rex mission (NASA, 2023b). However, if the aim of a space mining mission is to deliver large deposits back to Earth the technology available likely won't suffice. The best technological solution for mining one asteroid might differ to that of another due to locations in space, asteroid size, and type of resource. Similarly, the technology envisioned for mining space resources to enable deep space exploration will also differ as harvesting ice and decomposing it to hydrogen and oxygen presents a different set of challenges.

Requirements engineering for space mining

As the complexity surrounding the needs and constraints of space mining grows, the ability to capture this information and manage risks becomes critical. Requirements engineering will have an important role in translating, documenting, and communicating these factors across space mining missions and related projects.

The development of a consistent requirements engineering framework will be necessary to optimise communication between all people, and interfaces in the system. This will help facilitate the integration of all technological parts as they evolve and provides traceability for any changes as they arise. Moreover, through a standardised requirements engineering framework, inputs and responsibilities from all users and parties can be captured to ensure coordination towards a common goal.

As there will be many requirements, writing good requirements becomes important to achieve consistency and efficiency across the life of a project. Characteristics and attributes of good requirements are commonly identified as necessary, implementation independent, unambiguous, complete, singular, achievable, verifiable, and conforming (Walden *et al*, 2015). In addition to these, allocating testing methods, criticality, and traceability should also be captured for effective risk management.

Space mining requirements will be refined over time due to the complex nature of the project space. As a result, the requirements management system and related processes need to be adaptable and managed to ensure there is a single source of truth. Model-Based Systems Engineering (MBSE) tools will be required to manage the size of the data and prevent discrepancies that can arise from paper-based document approaches.

Through a requirements engineering framework, good requirements engineering practices, and the right tools, requirements engineering will be critical in ensuring effective communication and risk management for the development of a technological solution for space mining.

ESG FACTORS

The nature and complexity of engineering projects has significantly increased due to greater connectivity in the present world (Elliott, Deasley and Academy, 2007). Although space mining takes place off-Earth, the industry will be bound to have effects on everyday life. Therefore, when considering the impacts of the space mining industry, the wider implications must be assessed.

Environmental factors

A primary incentive for mining in space is the availability of critical minerals. Critical minerals are necessary in the modern world for technologies that include renewable energy, medicine, and national security (Australian Government Department of Industry, Science, and Resources, 2023). The opportunity to access them off-Earth offers an attractive possibility of further reducing the environmental footprint of mining them. However, despite the clear benefits, the consequences of mining off-Earth may turn out to be more significant than anticipated.

Despite being 384 400 km away and less than a third of the width of Earth, the moon directly effects tidal forces on Earth and maintains the Earth's rotation along its orbital axis (NASA, 2023a). These factors are critical for life on Earth, from stabilising Earth's climate, to supporting animal's navigation and migration patterns (Norevik *et al*, 2019). The composition of the lunar surface is still being studied for signs of life and providing clues on the history of Earth. With the effects or removing small or substantial masses from the moon remaining unknown, there is an overwhelming responsibility associated with ensuring that there are no unintended consequences from doing so.

Similarly, the composition of asteroids and meteorites is still being researched for answering questions surrounding Earth's history and the solar system. Although the direct relationships between Earth and these objects may not be as strong as that with the moon, there are still consequences that need to be considered. As of January 2022, the predicted that the amount of space debris orbiting Earth exceeded 9000 metric tonnes (NASA, 2020a) and that there is currently more space debris in orbit than operational satellites (ESA Space Debris Office, 2023).

Space mining operations will certainly both contribute and be impacted by the rising levels of space debris. With more debris left on the lunar surface and in orbit, the space around Earth is becoming increasingly congested. This creates hazards that can cause collisions with space objects and have adverse effects on mission success as well as technology such as satellites that are currently being utilised on Earth.

Social factors

Space is currently a 'no man's land', with questions surrounding regulations and processes yet to be resolved. It is therefore important to ask the question – is society ready for a space mining industry? At present, studies suggest whilst there is support for asteroid mining, there is less acceptance in the community for lunar mining (Hornsey *et al*, 2022).

From an economic perspective, if a substantial amount of critical minerals were successfully mined from space mining by one entity, it would likely result in significant wealth for a few individuals. However, the flow on effects from an increased supply on Earth, would have the potential to devalue the price of the resources, causing adverse economic effects. This would particularly be felt by developing countries that rely on mining and exports for the economy, especially if they are not equipped with the funding and skills to undertake space mining (Paikowsky and Tzezana, 2018). With the potential for disproportionate benefits across Earth, it therefore becomes important to ensure that the economy and supply chains are considered to ensure economic sustainability of the industry and wealth.

Governance factors

Accords and treaties have been developed for addressing key issues surrounding usage of outer space. One of the first set of treaties and principles was established by the Committee on the Peaceful Use of Outer Space (COPUOS) which all emphasise the need for international cooperation and space to be used for the benefit of all humankind (United Nations Office for Outer Space Affairs, 1966). These principles were built upon in the NASA Artemis Accords which similarly sought to establish guidelines that would ensure responsible and peaceful exploration of space (NASA, 2020b). The Artemis Accords have sparked both support for advancing cooperation in space, and debate as to whether they are too biased towards the interests of America and commercial exploitation (Boley and Byers, 2020). As a result, there remains a lack of official acceptance of the Artemis Accords from key countries leading in space exploration, including China and Russia. These countries are currently abiding to their own principles based on the construction of the International Lunar Research Station (ILRS) and are open to all interested countries (China National Space Administration, 2021).

Although these efforts provide a solid foundation for regulations regarding space exploration and utilisation, there is still further development required to ensure these efforts encompass space mining operations. Studies are being undertaken by individual entities including the Hague International Space Resources Governance Working Group (Xu and Su, 2020) and Secure World Foundation (Wilson and Vasile, 2023) to address some of the key issues. However, there is still a lack of unity and consistency from all interested parties. Without a unified set of guidelines, it becomes difficult to quantify ‘equitable benefit’ and easier for potential conflicts to arise. This results in further challenges to advance capabilities and enable a sustainable space mining industry for all humankind.

Space mining parties and stakeholders

For a successful project to take place, the needs and requirements of all stakeholders with an interest in the system should be addressed (Walden *et al*, 2015). In the context of space mining, it becomes evident that there are many diverse parties interested in space mining and its wider implications. These extend beyond government agencies and private companies and include financial and economic stakeholders, environmental experts, legal professionals, and the general public. Consulting these parties is critical in ensuring space mining practices are conducted ethically and in line with ESG standards. Moreover, through increased collaboration and sharing of knowledge the impacts and feasibility of space mining can be better understood, contributing to mission success and the realisation of a sustainable industry.

SYSTEM INTEGRATION

A system is an arrangement of parts that together exhibit qualities and behaviours that aren’t present in the parts themselves (Elliott, Deasley and Academy, 2007). Properties of a system emerge from the individual elements and more importantly the relationships and interactions between the parts (Walden *et al*, 2015).

For space mining, the interfaces and interactions are highly intricate and connected. From connections between technological elements, to interactions between different stakeholders, the problem space can quickly become challenging. Managing the problem space will therefore require individuals with specific skills and specialisations, as well as an appreciation for the problem holistically. Parts cannot be developed independently and must work together to achieve a successful system (Elliott, Deasley and Academy, 2007). For technological parts this includes coordination across all engineering and scientific disciplines. Verification and validation processes will need to take place to ensure integration of all parts and confirmation that all requirements are met.

Systems integration processes are already heavily adopted in a range of industries including space, Defence, and transport (Walden *et al*, 2015). Standards are available such as ISO 15288:2023 Systems and software engineering (International Organization for Standardization, 2023). Leveraging lessons learned from these industries and tailoring processes to space mining will play a key role in managing and addressing risks as they arise.

CONCLUSIONS

Space mining is a complex endeavour encompassed with incredible challenges and opportunities. As mining reserves on Earth continue to deplete, and constraints are imposed on deep space exploration, space mining offers a gateway to solving some of these issues currently encountered. At present, technology is continuing to develop at a rapid pace, however the technological solution that can enable space mining operations has not yet been proven. Furthermore, the challenges surrounding space mining extend beyond technology and encompass environmental, economic, social, and regulatory factors. Capturing and addressing these factors will play a key role in ensuring a sustainable industry can prosper. The gateway to space mining is filled with uncertainty and risk, but through a unified approach and adoption of systems engineering tools and processes, the challenges can be overcome, and benefits of a space mining industry realised.

ACKNOWLEDGEMENTS

The authors would like to thank and acknowledge Jon Sciortino and Martin Shadbolt for their ongoing support and knowledge.

REFERENCES

Atkinson, N, 2015. What are asteroids made of? [online], *phys.org*. Available from: <https://phys.org/news/2015–09-asteroids_1.html>

Australian Government Department of Industry, Science and Resources, 2023. Critical minerals [online], *Industry.gov.au*, Available from: <https://www.industry.gov.au/mining-oil-and-gas/minerals/critical-minerals>

Boley, A and Byers, M, 2020. U S policy puts the safe development of space at risk [online], *Science*, 3706513, pp 174–175. https://doi.org/10.1126/science.abd3402

China National Space Administration, 2021. International Lunar Research Station (ILRS) Guide for Partnership [online], *China National Space Administration*. Available from: <https://www.cnsa.gov.cn/english/n6465652/n6465653/c6812150/content.html>

Elliott, C, Deasley, P and Academy, R, 2007. *Creating systems that work: principles of engineering systems for the 21st century* (Royal Academy Of Engineering: London).

ESA Space Debris Office, 2023. ESA's Annual Space Environment Report [online]. Available from: <https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf>

Hornsey, M J, Fielding, K S, Harris, E A, Bain, P G, Grice, T and Chapman, C M, 2022. Protecting the Planet or Destroying the Universe? Understanding Reactions to Space Mining, *Sustainability*, 14(7):4119. https://doi.org/10.3390/su14074119

International Organization for Standardization, 2023. ISO/IEC/IEEE, 15288:2023 Systems and software engineering [online]. Available from: <https://www.iso.org/standard/81702.html>

NASA, 2020a. ARES – Orbital Debris Program Office, Frequently Asked Questions [online]. *NASA*, Available from: <https://orbitaldebris.jsc.nasa.gov/faq/>

NASA, 2020b. NASA: Artemis Accords [online], *NASA.* Available from: <https://www.nasa.gov/specials/artemis-accords/index.html>

NASA, 2023a. Moon: Facts [online], *NASA Science.* Available from: <https://science.nasa.gov/moon/facts/>

NASA, 2023b. OSIRIS-REx [online], *NASA Science.* Available from: <https://science.nasa.gov/mission/osiris-rex/>

Norevik, G, Åkesson, S, Andersson, A, Bäckman, J and Hedenström, A, 2019. The lunar cycle drives migration of a nocturnal bird, *PLOS Biology*, 17(10):e3000456. https://doi.org/10.1371/journal.pbio.3000456

Paikowsky, D and Tzezana, R, 2018. The politics of space mining – An account of a simulation game, *Acta Astronautica*, 142:10–17. https://doi.org/10.1016/j.actaastro.2017.10.016

United Nations Office for Outer Space Affairs, 1966. The Outer Space Treaty [online], *UNOOSA*. Available from: <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html>

Walden, D D, Roedler, G J, Forsberg, K, R Douglas Hamelin, Shortell, T M and Council, I, 2015. *Systems engineering handbook: a guide for system life cycle processes and activities*, 4th ed, (Wiley: Hoboken).

Wilson, A and Vasile, M, 2023. The space sustainability paradox, *Journal of Cleaner Production*, 423:138869–138869. https://doi.org/10.1016/j.jclepro.2023.138869

Xu, F and Su, J, 2020. New Elements in the Hague Space Resources Governance Working Group's Building Blocks, *Space Policy*, 53,:101386. https://doi.org/10.1016/j.spacepol.2020.101386

Investigating the impact of royalties on commercial lunar ice mining

B McKeown[1], A G Dempster[2], S Saydam[3] and J Coulton[4]

1. FAusIMM, PhD Candidate, Australian Centre for Space Engineering Research, UNSW, Sydney NSW 2052. Email: b.mckeown@unsw.edu.au
2. Professor, Australian Centre for Space Engineering Research, UNSW, Sydney NSW 2052. Email: a.dempster@unsw.edu.au
3. Professor, Australian Centre for Space Engineering Research, UNSW, Sydney NSW 2052. Email: s.saydam@unsw.edu.au
4. Senior Lecturer, UNSW Business School, UNSW, Sydney NSW 2052. Email: j.coulton@unsw.edu.au

INTRODUCTION

This research investigates the potential economic impact of introducing a royalty system on a conceptual lunar ice mining operation, should such activities eventuate, and the possible global benefits royalties could generate over a 50 year period.

DISCUSSION

The extraction of space resources, particularly lunar water ice, is poised to play a critical role in a burgeoning space economy. This ice, initially vital for life support, could eventually be used to produce rocket propellant, marking a significant step in space exploration and space resource utilisation. Current research predominantly focuses on the technical feasibility of such space resource ventures, often overlooking commercial aspects vital for the sustainable development of a space economy. A major consideration in this area is addressing the 'Benefit of Mankind' issue. This revolves around how benefits from space resource activities should be equitably shared among humanity, a topic of ongoing debate since the signing of the Outer Space Treaty (OST) in 1968. The OST did not envisage the potential exploitation of space resources in any form, leading to significant ambiguity as to the legal standing of such activities. The Moon Agreement negotiated subsequently, attempted to provide more clarity on the rights and obligations of State Parties with respect to space resource activities, but did not secure widespread acceptance. Recent attempts to clarify the legal and governance position around space resources comes from groups such as the Hague Working Group (HWG) who proposed non-monetary benefit sharing mechanisms from space resource activities through capacity sharing for example, and countries such as the US, Luxembourg and Japan who have enacted unilateral legislation around space resource activity, without addressing the 'benefit of mankind' issue. The Artemis Accords, now signed by 36 countries, is a series of bi-lateral agreements focused on the development of the Artemis Program, including the facilitation of space resource activities. However, these again do not address the issue of benefit sharing from space resources. The latest initiative is through the Legal Subcommittee of the UN Committee on the Peaceful Uses of Outer Space (COPUOS) which has set-up a working group with a five year mandate to explore options for legal principles for space resource activity. The mandate for this COPUOS working group includes the facilitation of sharing by all States of benefits from space resources. Whilst it is not yet clear whether this would be through monetary or non-monetary means, it is possible that a royalty type mechanism could be proposed for such benefit sharing.

Understanding the relevant fiscal framework is crucial for terrestrial mining activities. Typically, such fiscal frameworks consist of a combination of taxes and royalties, which can vary significantly depending on jurisdiction. Often such a fiscal 'burden' can be significant and can greatly impact the economic viability of mining projects, with the Effective Tax Rate for a mining project typically ranging from 40–60 per cent (Otto *et al*, 2006). Understanding the impact of a potential fiscal framework could be equally important for commercial space resource extraction if there is the potential for such a fiscal regime being applied to space resource activity. This study therefore considers the impact of a hypothetical royalty (and tax) regime being applied to commercial space resource activity.

The study is grounded in a financial model based on a hypothetical lunar ice mining project detailed in the report generated for the NASA Innovative Advanced Concepts (NIAC) Program titled 'Thermal Mining of Ices on Cold Solar System Bodies' (Sowers, 2020). The study explores various combinations of ad valorem royalties and tax rates to assess their impact on key investment metrics for the project in order to determine the highest royalty rate the project could sustain before becoming commercially unviable. Additionally, the study evaluates the potential global benefits that could be generated by such royalties, applying various industry growth rate assumptions over a 50 year period. These conceptual benefits were then allocated on a per capita basis to the populations of four countries, each representing a different World Bank economic classification. This follows the precedent set by the International Seabed Authority under the UN Convention on the Law of the Sea (UNCLOS) for allocating benefits from potential deep sea mining activities in international waters. The findings of the study indicate that the implementation of ad valorem royalties could significantly influence the economic viability of a lunar ice mining project, with indications being that such a project may only be able to support a relatively low level of royalty at best, depending on the tax rate assumptions used (refer to Figure 1). Moreover, the benefits accrued over 50 years appear minimal on a per capita basis, even for countries classified as Low Income by the World Bank (refer to Figure 2). This highlights the need for a carefully structured economic approach to space resource extraction, ensuring fair distribution and sustainable development.

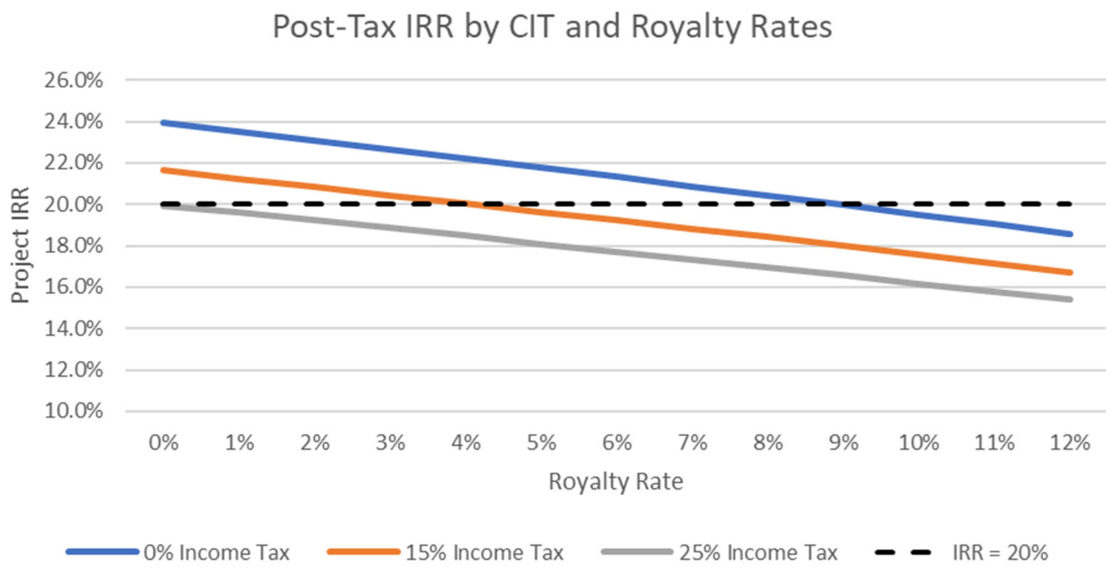


FIG 1 – Project post tax IRR by corporate income tax (CIT) rate and royalty rate.

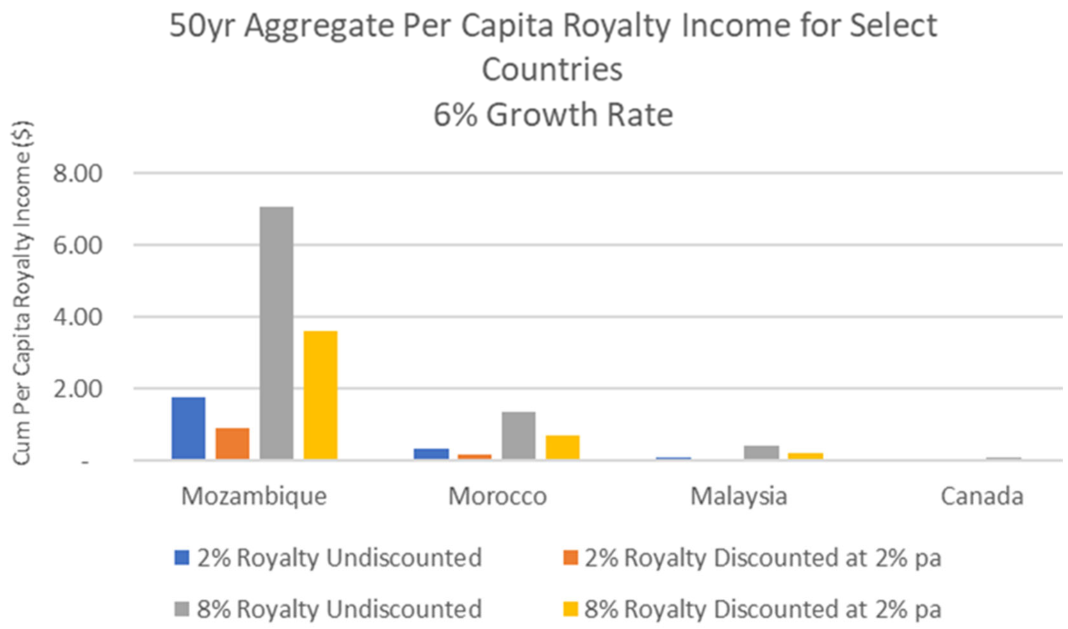


FIG 2 – 50 year aggregate royalty revenue per capita for select countries at 6 per cent growth rate.

CONCLUSION

The study concludes that it may be more appropriate to consider non-monetary variants of benefit sharing, rather than monetary benefit sharing mechanisms that could impact the economic viable of commercial space resource projects, and therefore the development of a sustainable space resource industry.

This extended abstract draws on findings in the authors' research article titled: 'Commercial Lunar Ice Mining: Is There a Role For Royalties?' (McKeown *et al*, 2022).

REFERENCES

McKeown, B, Dempster, A G, Saydam, S and Coulton, J, 2022. Commercial Lunar Ice Mining: Is There a Role for Royalties?, *Space Policy*, 101525.

Otto, J, Andrews, C, Cawood, F, Doggett, M, Guj, P, Stermole, F, Stermole, J and Tilton, J, 2006. Mining royalties: a global study of their impact on investors, government, and civil society (English), *Directions in development; energy and mining* (World Bank Group: Washington DC).

Sowers, G, 2020. NASA Innovative Advanced Concepts (NIAC) Phase I study: Thermal Mining of Ices on Cold Solar System Bodies, Colorado School of Mines.

Key technology indicators that will influence mining method selection for future mines

S Nowosad[1] and O Langefeld[2]

1. Clausthal University of Technology, Clausthal-Zellerfeld 38678, Germany.
   Email: sandra.nowosad@tu-clausthal.de
2. Professor, Clausthal University of Technology, Clausthal-Zellerfeld 38678, Germany.
   Email: oliver.langefeld@tu-clausthal.de

ABSTRACT

The mining industry has undergone a profound and transformative shift in recent years, driven by the rapid advancement of emerging technologies such as automation, digitalisation, and electrification. These technological innovations have not only revolutionised operational efficiency and productivity but have also introduced an imperative need for new and innovative approaches to conducting mining activities. Specifically, the mines of the future face a new series of complex challenges when planning and developing greenfield or brownfield mining projects in the 21st century. These challenges include greater operational depths, higher seismicity levels, higher rock temperatures, increased environmental constraints and sustainability requirements, a higher degree of interoperability, lack of skilled workforce, and the need for sustainable and eco-friendly mining practices. Consequently, there is an essential need to formulate novel strategies and robust planning methodologies that re-evaluate how mines are planned, executed, and managed, from the early exploration stages to the post-mining era and the consequent uses of mine sites. This research focuses on identifying the factors influencing the implementation of modern technologies, such as autonomous machinery in mining operations, and their impact on mining method selection and long-term mine planning. The findings underscore a crucial need for a paradigm shift in how mines are planned and developed, going beyond mining method selection, which primarily focuses on geological and economic factors, and must evolve to incorporate the multifaceted implications of modern mining operations.

METHODOLOGY

This research project employed a multifaceted three-step methodology to comprehensively analyse the influence of modern technologies in mining. First, a thorough review of existing literature, encompassing academic publications, industry reports, and case studies, was conducted to identify research gaps and establish the current state-of-the-art. Second, in-depth personal interviews were carried out with leading industry representatives, providing valuable practical insights and real-world context to the study. Finally, a comprehensive global assessment encompassing both metal and coalmines was undertaken to evaluate the widespread implementation of autonomous machinery in operations worldwide, offering a holistic view of current practices and emerging trends in the mining industry. The three-step methodology was used to define the influencing factors for the implementation of technology in underground mining operations.

Analysis of Contemporary Literature: A comprehensive review of existing literature, including academic papers, industry reports, and case studies, was conducted. This review aimed to understand the current state of modern mining method selection, regional framework for long-term mine planning, regional framework for feasibility studies and, application of modern technologies in mining operations, existing frameworks and their limitations setting a strong focus on the deployment of autonomous machinery in underground mining operations. Moreover, a semantic and gap analysis was conducted to confirm research gaps. The qualitative assessment considered factors such as interoperability, capital cost demand, related operational costs, technology readiness level, safety concerns, and emissions, as well as public case studies, reports, and learned lessons from leading mining companies such as LKAB and Hecla and leading original machinery manufacturers (OEMs).

Personal Interviews: In the period of March 23 to March 24, in-depth interviews were conducted with around 30 representatives from the mining industry, including mining engineers, project and technology managers such as OEMs and original technology manufacturers (OTMs). These interviews provided valuable insights into practical experiences, challenges faced along implementation, and decision-making processes related to autonomous machinery operational readiness.

Global Assessment: A comprehensive assessment of global underground mining activities was conducted and built the Global Mine Tracker (GMT) database. GMT is based on an open-source database encompassing over 1000 mining projects across surface and underground operations worldwide (fineprint.global). To facilitate further analysis, the database was supplemented with additional parameters, including the primary and secondary mining methods employed, ESG (Environmental, Social, and Governance) advocacy, reports and code types utilised in the feasibility phase, automation initiatives, and innovation strategies. The automation initiatives were classified based on IBMs three types of automation: basic, process and intelligent automation.

KEY FINDINGS

Gap analysis focused on underground mining methods, parameters, and long-term mine planning and used the software VOSviewer to generate visual maps based on an own library of selected research papers and journals. These maps display clusters of related research topics categorised by colour whereby gaps or sparse areas indicate potential opportunities for new research. Furthermore, the closer two themes are placed to each other, the stronger their relatedness is. By analysing these visualisations, researchers can identify underexplored topics or emerging fields in underground mining where further investigation could be valuable (van Eck and Waltman, 2023).

A first analysis included classified papers filtered by using the keywords mining method, mining method selection and indicators of the last 24 years a seen on the left side of Figure 1. Clusters of related research topics were identified, with sparse areas indicating that these two crucial aspects—method selection and feature selection—are often studied together and sparsely rather than in an integrated manner, therefore a marked distance in the showcased network. This distance highlights the need for comprehensive research to bring these areas closer, promoting a holistic approach to improving mining method selection through a more extensive feature selection strategy. Mining method selection is crucial for the success and efficiency of mining operations, as it determines the overall approach to resource extraction. A second analysis was conducted based on a more extensive set of keywords as displayed in the right side of Figure 1, where a variety of more than 50 factors where identified in relation with mine planning, long-term mine planning and technology implementation. The identified factors were classified and analysed to build the first baseline for assessment and discussion.

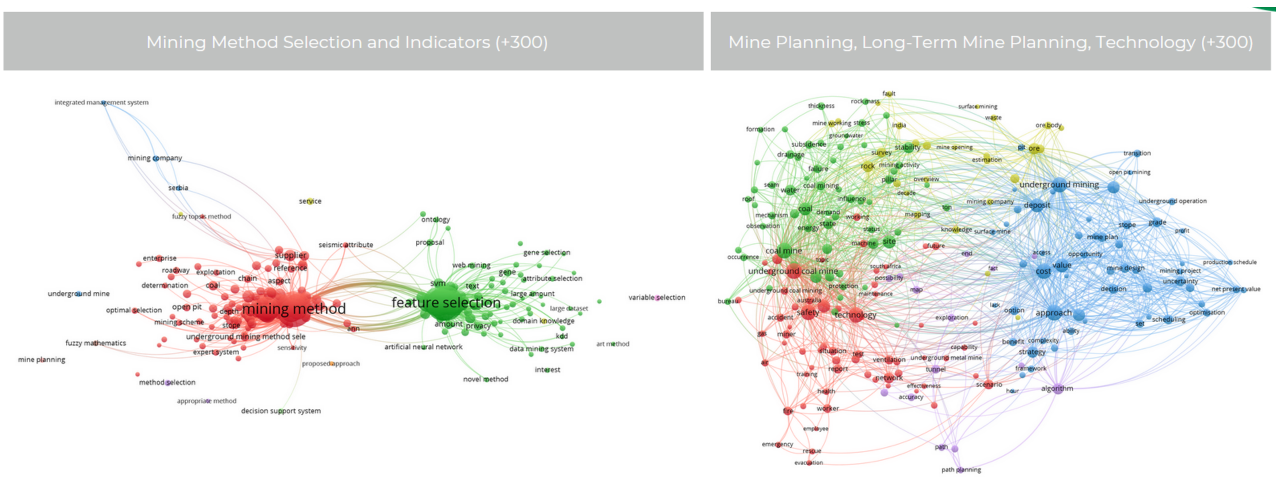


FIG 1 – Term co-occurrence networks results of the semantic search and gap analysis by Vosviewer.

Feature selection, which involves identifying the most relevant factors and parameters, forms the foundation of this decision-making process. However, this analysis has shown that the contemporary approach of analysing specific factors, mostly related to the geological and geometrical characteristics of the orebody, is insufficient for the proper integration of modern technologies in mining operations. For instance, a study by Alpay and Yavuz (2009) emphasises the need for a comprehensive assessment that includes economic, technical, and environmental criteria for mining method selection. Similarly, research by Eskandari, Ghorbani and Samani (2021) highlights that integrating advanced decision-making frameworks, such as fuzzy logic and multi-criteria decision analysis, can improve the selection process by considering a broader range of variables. However, despite the proven effectiveness of these methods, most research involving advanced classification approaches still focuses solely on the Key Deposit Indicators (KDI) defined by Nieto (2010), based on Nicholas *et al* (1992, 1981). A contemporary challenging framework for mining operations and the need for integrating parameters that adequately address the challenges of modern mining activities and technologies defined that the impact of integrating a wider variety of factors has a higher impact in long-term mine planning as solely in the mining method selection. Therefore, this research identified four major groups of factors, namely indicators, and proposes a four-layer approach for a dynamic long-term mine planning approach (see Figure 2). The approach enhances the iterative assessment of the four layers in sequence for long-term mine planning when assessing technology implementations and before selecting a one final mining method.

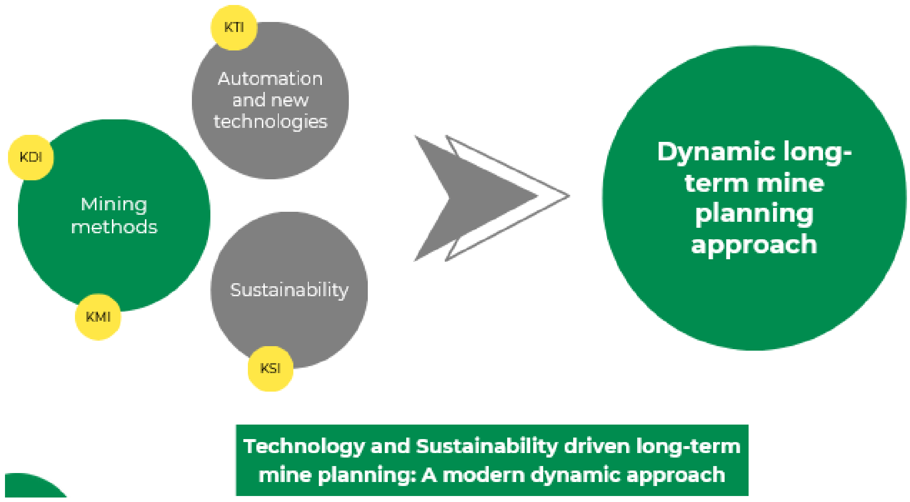


FIG 2 – Framework of implementation of the technology and sustainability indicators as part of the dynamic long-term mine planning approach.

Nieto (2010) stated that mining method selection is traditionally based primarily on the suitability of orebody characteristics or Key Deposit Indicators (KDI), setting the first layer in mining method selection, and factors related to productivity and operability are introduced as a second layer of assessment named Key Mining Method Indicators (KMI). An initiative by Nieto (2010) introduced the Key Mining Indicators (KMI), which were used to select the method that best matches expected operational productivity in a second assessment layer. Furthermore, the challenges associated with applying and deploying new technologies in underground mining were identified and introduced as Key Technology Indicators (KTI) in a third assessment layer. Finally, sustainability factors and the impact of technology is assessed in a fourth layer comprising Key Sustainability Indicators (KSI). A general overview of the proposed indicators is provided in Table 1. Only by assessing autonomous machinery deployment, new elements such as the extension of supporting infrastructure, quality of network connectivity, layout design, and safety considerations gain higher relevance and directly influence mine planning and layout design, and therefore, in mining method selection for future mines. This research especially targets greenfield project planners and developers. It encourages them to consider modern technologies' requirements, benefits, and challenges by introducing the iterative dynamic approach and four layers of indicators as relevant components in underground mining method selection processes. Finally, this paper introduces KTI as a third layer in the decision-making process to optimise the extraction of metals. Based on publicly accessible information, two mining projects were used as case studies, one in Ecuador and one in Australia. They delineated the advantages and disadvantages associated with the introduction of KTI. Moreover, this research identified how the technology implementation affects underground mining operations beyond the decision of a suitable mining method and that future research should focus on integrating and assessing its implications in the complete life cycle of mining projects through dynamic and integrative mine planning practices.

TABLE 1

Base factors or indicators for a dynamic long-term mina planning approach. The provided lists do not represent a relevance order (*modified after Nieto (2010) and Nicholas *et al* (1992)).

1st Layer **Key deposit indicators***	**2nd Layer** **Key mining method indicators***	**3rd Layer** **Key technology indicators**	**4th Layer** **Key sustainability indicators**
Ore strength (RMR, RSS Ore) Host rock strength (RMR, RSS Hanging Wall, RMR Footwall) Deposit shape Deposit plunge Deposit size Deposit thickness Deposit depth Ore grade Ore uniformity RMR: Rock Mass Rating, RSS: Rock Substance Strength	Operating cost Capital investment Development Dilution Subsidence Production rate Productivity Development rate Depth capacity Selectivity Recovery Flexibility Stability of openings Health and safety Mechanisation Ventilation Continuous Gravity assistance	Productivity Increased level of efficiency Mine Design considerations Impact on recovery Impact on dilution Flexibility to changing conditions Selectivity and consistency Concentration or dispersion of workings Ability to mechanise and automate Capital investment Associated labour intensity-> Workforce Regulations Ownership models Safety hazards (mixed working areas) Supporting infrastructure demand Reduction of operative costs (personal and maintenance) Compatibility with mine design (zoning)	Water consumption Energy consumption CO_2 emissions (generated/reduced) Impact on production throughout Post-Mining economic potential Circularity potential of resources

Furthermore, not only the operational readiness of the technologies has been taken into consideration in the selection of the factors or indicators, also the results of the global assessment and information made through GMT have provided relevant insights when assessing the operational readiness of a technology. GMT revealed that over 150 projects involved a transition or are undergoing transition from surface to underground operations. Regarding underground mining methods, this study can state that the three widely used methods worldwide are room and pillar for coalmines, followed by longhole stoping and cut-and-fill for hard rock metal mines. Special analysis regarding innovation and automation initiatives highlighted Australia's significant role in the technological transformation as the leader in initiatives and implementations within the global mining industry, see Figure 3. Additionally, the study determined the industry's technology readiness level, with 61 per cent of the underground mines incorporating automation initiatives mostly covering basic and process automation, meanwhile less than 10 per cent would count with a type of intelligent automation initiative. The GMT database proved to be a valuable tool, and the findings are used as a foundation for further analysis focusing on longhole stoping and cut-and fill operations.

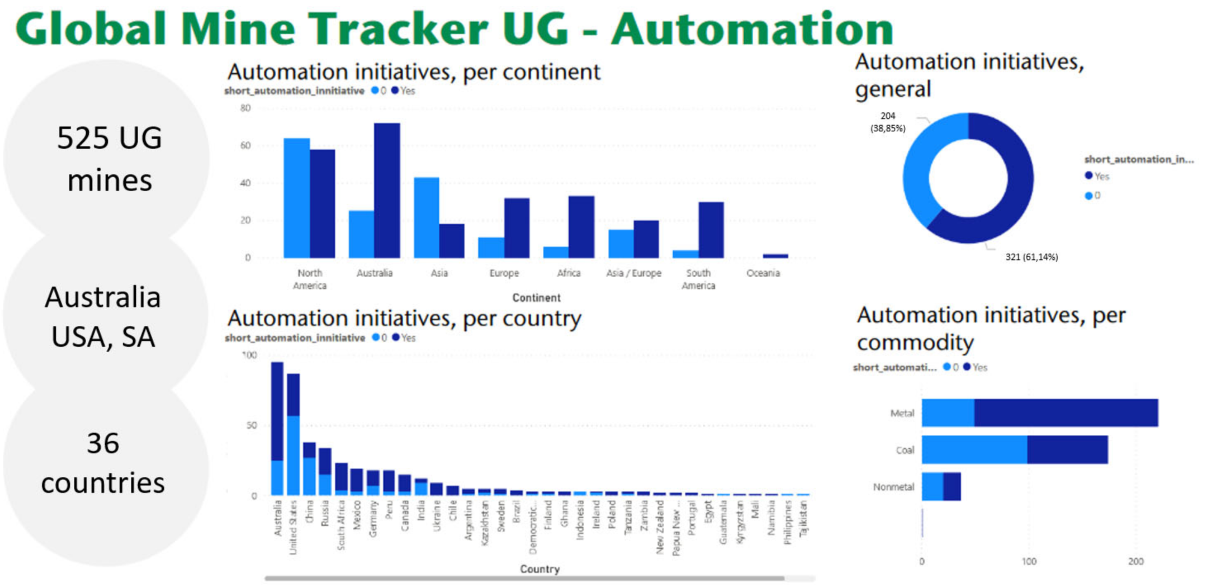


FIG 3 – Overview of the results of the automation initiatives assessment of Global Mine Tracker (GMT) for underground operations updated to June 24.

OUTLOOK

This study examines the mining industry's technological readiness level, identifying global challenges hindering technology implementation. By recognising the need to guide the industry towards a new era of mining, the research introduces and defines Key Technology Indicators poised to influence future mining method assessment. These KTIs systematically integrate the constraints and requirements of emerging technologies, such as automation, while upholding paramount considerations of safety, environmental responsibility, and sustainable resource extraction. Currently, a pairwise comparison method, involving a diverse group of stakeholders, is being employed to categorise and rank these KTIs and KSIs based on their relevance and impact to the mine planning process. This prioritisation process aims to inform and shape long-term mine planning decisions for modern and future mines.

ACKNOWLEDGEMENT

The authors would like to express appreciation for the support of all interview participants for dedicating their time, sharing the initiatives of the companies they represent and their experience.

REFERENCES

Alpay, S and Yavuz, M, 2009. A new approach in selection of underground mining method, *Journal of Mining Science*, 45(2):202–210.

Eskandari, M, Ghorbani, M and Samani, B, 2021. A comprehensive approach for underground mining method selection using fuzzy logic and multi-criteria decision making, *International Journal of Mining Science and Technology*, 31(4):547–555.

Nicholas, D E, 1981. *Method Selection – A Numerical Approach, Design and Operation of Caving and Sublevel Stoping Mines* (ed: D Stewart), chap 4, pp 39–53 (SME-AIME: New York).

Nicholas, D E, 1992. Selection method, *SME Mining Engineering Handbook* (ed: H L Hartman), 2nd ed, pp 2090–2106 (Society for Mining Engineering, Metallurgy and Exploration, Inc).

Nieto, A, 2010. Key Deposit Indicators (KDI) and Key Mining Method Indicators (KMI) in Underground Mining Method Selection, *Transactions of the Institution of Mining and Metallurgy, Section A: Mining Technology*, 328:381–396.

Van Eck, N J and Waltman, L, 2023. VOSviewer Manual.

Real time assessment of water content in icy regolith by analysing drilling parameters

J Rostami[1], D Joshi[2], A Eustes[3] and M Karakus[4]

1. Professor, Mining Engineering, Colorado School of Mines, Golden CO, USA. Email: rostami@mines.edu
2. Data Scientist, Quantum Capital Group, Houston TX, USA. Email: joshi.deep2010@gmail.com
3. Emeritus Professor, Petroleum Eng, Colorado School of Mines, Golden CO, USA. Email: aeustes@mines.edu
4. School of Chemical Engineering, The University of Adelaide, Adelaide SA 5005. Email: murat.karakus@adelaide.edu.au

ABSTRACT

The first target of mining activities on the surface of the moon is to find and extract water from the icy regolith on the moon. A test drilling unit was designed and fabricated under a NASA Early Stage Innovation (ESI) grant. A high-frequency data acquisition system was used to record drilling responses at 1000 Hz. Parameters like weight on bit (WOB), torque, rev/min, rate of penetration (ROP), mechanical specific energy (MSE), field penetration index (FPI), and the uniaxial compressive strength (UCS) were recorded for 40 boreholes in the analog samples made of regolith simulant and specialised cement. Development of the AI system and machine learning (ML) algorithms for analysis of data to evaluate strength and hence water content of icy regolith required a large data set. In this case, the data set comprising of more than one billion data points recorded while drilling into various analogue samples and cryogenic lunar formations to optimise power consumption and make bit wear adjustment during drilling operations. The tests were also repeated in the samples of icy regolith at various water content at -190°C to verify the ability of the algorithms to analyse the data and to estimate the strength of the frozen formation and hence water content. The paper will discuss the objectives and methodologies used in the project and reviews the testing program and the machine learning (ML) algorithms ability to identify various formations along the exploration boreholes.

INTRODUCTION

Water has been referred to as the ‘oil’ of space due to its pivotal role in the space economy. The water found on the Moon or any other planetary body can be utilised for a variety of purposes, from human consumption to in-space manufacturing. However, the most significant use of water on these planetary bodies is as fuel. Water can be separated into oxygen and hydrogen, which can then be used as rocket fuel or be used in fuel cells to power various vehicles and equipment.

The presence of water on the Moon has been established through remote observations from orbital satellites. The first direct evidence of water and other volatile substances on the Moon was obtained through the Lunar Crater Observation and Sensing Satellite (LCROSS). In this mission, a Centaur rocket upper stage was crashed into the Cabeus crater in October 2009, and the resulting ejecta plume was observed by the Lunar Reconnaissance Orbiter (LRO). Analysis of the ejecta plume indicated a water content of 5.6 ± 2.9 per cent by mass (Colaprete *et al,* 2016).

Recently, several studies have proposed various strategies for economically mining and processing the water-ice from the permanently shadowed regions on the Moon (Neal *et al*, 2024; Zhang *et al*, 2023; Radl *et al*, 2023). However, not much is known about the geotechnical properties of the water-ice in the lunar subsurface. The aim of this research was to develop complex geotechnical characterisation algorithms that can estimate the geotechnical properties of water-bearing formations in the lunar subsurface, in particular its strength from drilling parameters. The properties of icy-regolith was linked to the water content and temperature in this project, leading to the ability to estimate water content from drilling data. The drilling algorithms used in terrestrial drilling operations were adapted for use in upcoming lunar missions that include a drilling system. The result is the system that can evaluate the water content of the icy regolith in real time, without the need to sample the formations, transportation to a lab, and testing to make such assessment. This step is critical for site investigation to measure the volume of rock for any mine planning purposes.

METHODOLOGY

Based on the designs of drilling systems proposed for lunar exploration, a test drilling unit was designed and fabricated (Figure 1). Several high and low-porosity concrete samples, both homogeneous and layered, were prepared as analogue equivalent for lunar water-ice samples with varying strength, form, and water content. The drilling unit was equipped with a high-frequency data acquisition system that recorded key drilling measurements such as Weight on Bit (WOB), Revolutions Per Minute (rev/min), depth/drilling speed, and Torque. Workflows were developed to calculate other key drilling parameters such as Mechanical Specific Energy (MSE) and Field Penetration Index (FPI). These drilling measurements were used to construct complex algorithms to estimate the rig state, calculate formation thickness, identify the form of water-ice, characterise the porosity of the formation (high versus low porosity), predict drilling dysfunctions, calculate the Uniaxial Compressive Strength (UCS) of the formation being drilled, and estimate the water content of the formation. Additionally, a workflow was developed to prepare different forms of water-ice samples with lunar simulants and test high and low porosity lunar simulant samples, which were tested at -190°C to simulate drilling operations under lunar conditions.

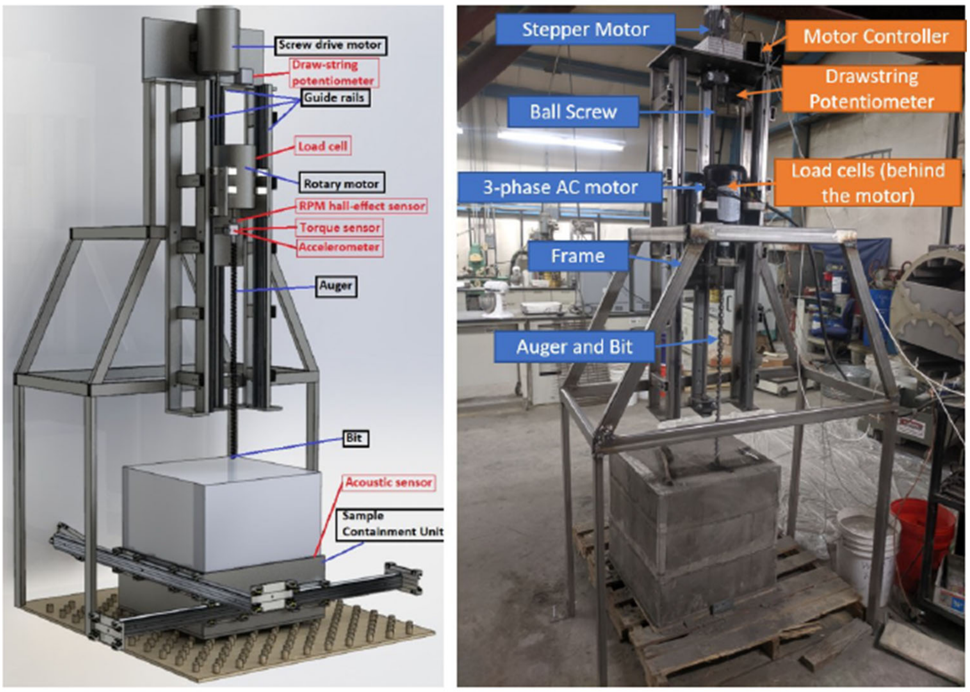


FIG 1 – Schematic drawing and picture of the drilling unit used in this study.

RESULTS

The machine learning algorithms were blind tested on both analogue and cryogenic samples. A test matrix was developed to simulate drilling operations in complex simulated formations and test the machine learning algorithms. The Figure 2 illustrates the performance of the machine learning algorithms in a wide range of samples and conditions from the blind tests. Figure 3 shows the result of using algorithm on blind synthetic data where real signals from different tests were assembled as part of a virtual borehole and fed to the ML algorithm and the program could identify the formations and transition between the formations. The test shows the ability of the algorithm to receive real time data from the drill and be able to classify the drill state (issues or steady state drilling), classify material into high or low porosity, and evaluate the strength of the formation, and if the formation is identified to be compacted low porosity icy regolith, to estimate the water content.

In addition, optimisation algorithms were developed to optimise drilling in real-time by controlling the WOB and rev/min to minimise the drilling power, Mechanical Specific Energy, and reduce drilling dysfunctions. Additional information can be found in Joshi (2021).

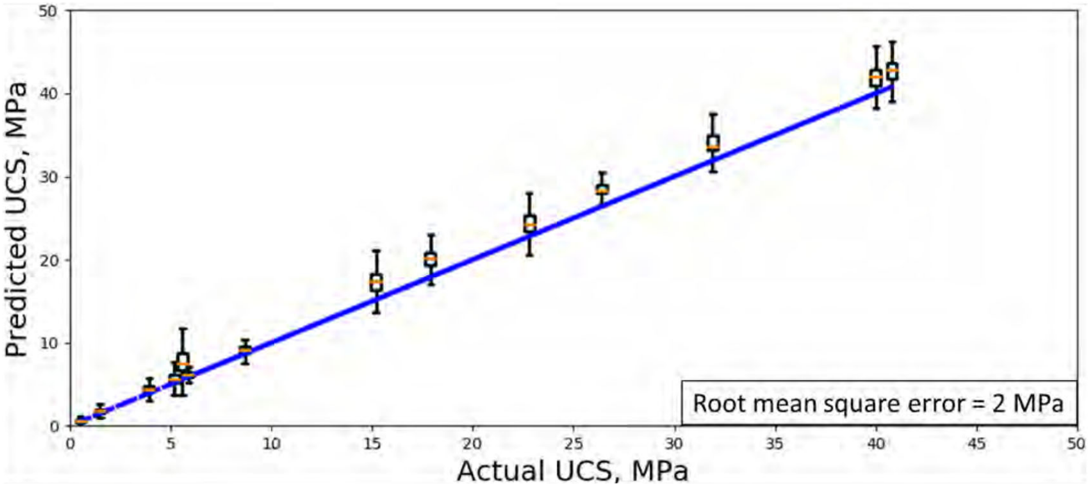


FIG 2 – Result of the ML algorithms for predicting the strength of formations on real time basis

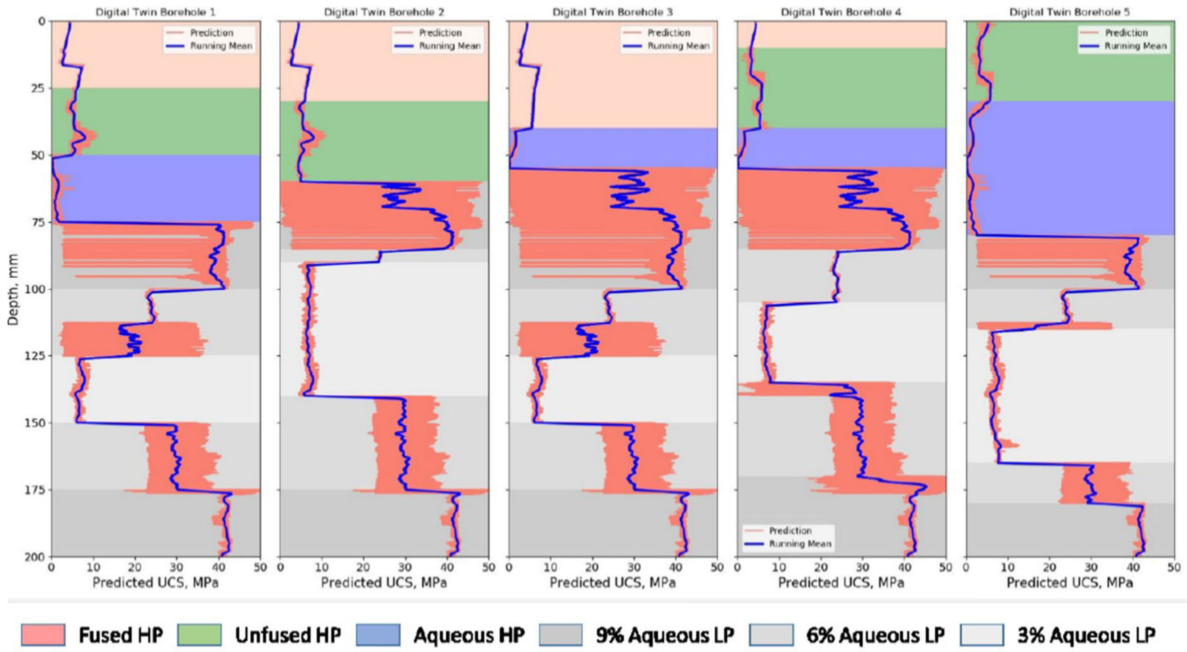


FIG 3 – Result of the ML algorithms and estimation of the formation strength in different samples.

REFERENCES

Colaprete, A, 2016. Resource Prospector: Evaluating the ISRU Potential or the Lunar Poles, LEAG.

Joshi, D R, 2021. Real-time characterization of water-bearing lunar regolith while drilling on the moon, PhD Thesis, Colorado School of Mines.

Neal, C, Salmeri, A, Abbud-Madrid, A, Carpenter, J, Colaprete, A, Hibbitts, K, Kleinhenz, J, Link, M and Sanders, G, 2024. The Moon needs an international lunar resource prospecting campaign, *Acta Astronautica*, vol 214.

Radl, A, Neumann, K M, Wotruba, H, Clausen, E and Friedrich, B, 2023. From lunar regolith to oxygen and structural materials: an integrated conceptual design, *CEAS Space Journal*, 15:585–595.

Zhang, P, Dai, W, Niu, R, Zhang, G, Liu, G, Liu, X, Bo, Z, Wang, Z, Zheng, H, Liu, C, Yang, H, Bai, Y, Zhang, Y, Yan, D, Zhou, D, and Gao, M, 2023. Overview of the Lunar In Situ Resource Utilization Techniques for Future Lunar Missions, *Space: Science and Technology*, vol 3.

Ice-drilling and ground characterisation on the moon for space mining

B H Ryu[1], J Lee[2], H Jin[3] and H S Shin[4]

1. Senior Researcher, Korea Institute of Civil Engineering and Building Technology, Republic of Korea. Email: tnt306@kict.re.kr
2. Research Fellow, Korea Institute of Civil Engineering and Building Technology, Republic of Korea. Email: jlee@kict.re.kr
3. Senior Researcher, Korea Institute of Civil Engineering and Building Technology, Republic of Korea. Email: hyunwoo.jin@kict.re.kr
4. Senior Research Fellow, Korea Institute of Civil Engineering and Building Technology, Republic of Korea. Email: hyushin@kict.re.kr

ABSTRACT

Prospecting ice on the Moon necessitates drilling systems to obtain subsurface samples and measure the composition of ice deposits. Landers and rovers equipped with drilling equipment are essential for analysing ice and subsurface resources located at the Moon's poles. These devices must be small, lightweight, low-power, highly efficient, and high-performance units to function properly in the extreme conditions of the lunar environment. Researchers have developed a prototype drilling apparatus capable of operating in atmospheric and cold environments. A newly developed drilling system in Korea, capable of performing not only sampling but also subsurface investigation, is introduced.

INTRODUCTION

In the global pursuit of space advancement, nations and corporations are actively engaged in lunar exploration, driven not only by the Moon's enigmatic allure but also by its profound implications for humanity's future (Ju, 2016). With Earth's finite resources depleting at a pace influenced by economic growth, the notion of perpetual reliance on our planet's resources has become obsolete. Consequently, efforts are underway to conserve resources through innovations like alternative energy and materials, while simultaneously exploring extraterrestrial resource acquisition methods (Ju, 2016).

The potential to extract oxygen from lunar ice holds transformative promise for both manned and deep space exploration, positioning the Moon as a crucial outpost for humanity's voyage into the cosmos (Thomson *et al*, 2013). Despite the challenges posed by the lunar south pole's rugged terrain and communication obstacles compared to equatorial regions, its appeal lies in the presence of water, essential for life and ripe for exploration.

Major spacefaring nations, including the United States and China, have unveiled ambitious lunar missions, with the lunar south pole earmarked as a strategic landing site under initiatives like NASA's 'Artemis Plan' (Ju, 2016). Concurrently, projects such as the Space Resources Exploration Project, jointly undertaken by NASA and CAST, underscore the need for robust drilling equipment capable of withstanding extreme space environments (Ju, 2016). This necessitates the development of drilling apparatuses that are ultra-lightweight, compact, and capable of unmanned operation with minimal power consumption during transit from Earth to celestial bodies.

In alignment with the burgeoning trend of international space missions, this study pioneers the creation of a novel drilling rig tailored for space resource exploration. Additionally, it introduces an evaluation methodology that directly estimates the uniaxial compressive strength of lunar terrain using data gleaned from this specialised equipment (Ju, 2016).

LUNAR GROUND DRILLING RIG

NASA achieved the first manned lunar landing in 1971 with Apollo 15, marking the inception of successful lunar surface drilling. The drilling apparatus utilised was the ALSD (Apollo Lunar Surface Drill), a battery-powered handheld tool employed by the Apollo 15 crew for drilling operations. Over the subsequent four decades, NASA's drilling technology underwent substantial advancements through rigorous research and development, notably with the creation of The Icebreaker Drill, as illustrated in Figure 1, developed by Honeybee Robotics, Ltd., in the United States (Zacny *et al,* 2012). This drilling equipment was designed to probe ice-rich areas of Mars in search of signs of life.

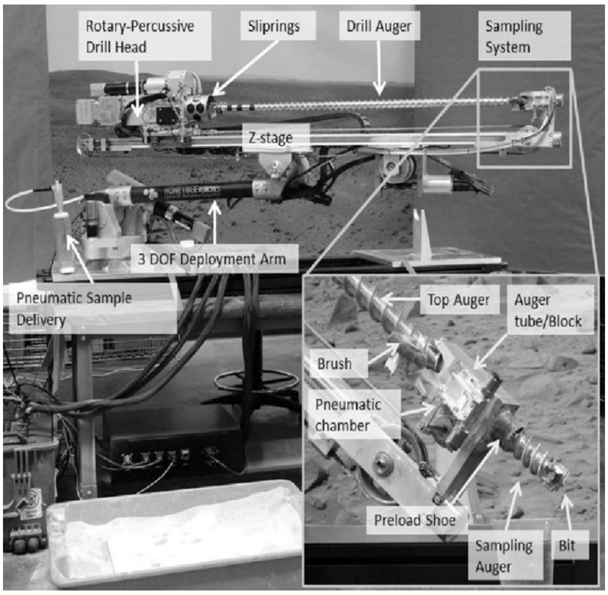


FIG 1 – Components of the Icebreaker drill (Zacny *et al,* 2012)

Considering the hostile drilling conditions on Mars, characterised by low gravity, reduced atmospheric pressure, limited electrical energy, and challenges in employing cutting fluid, the equipment aimed to achieve a performance milestone of drilling to a depth of 1 m within an hour, utilising 100 W of power and generating less than 100 N of thrust. This goal was accomplished through rigorous vacuum chamber experiments conducted in a Mars-like environment (Zacny *et al,* 2012).

The China Academy of Space Technology (CAST) became the third country to achieve a lunar landing in 2013 with its lunar exploration satellite Chang'e 3. In 2020, the unmanned lunar rover Chang'e 5 was launched to collect samples from the Moon and return utilising the drilling rig depicted in Figure 2. Departing from the Wenchang Space Launch Center in Hainan Province, China, Chang'e 5 touched down in the 'Sea of Storms', a north-western lunar plain, retrieving approximately 2 kg of soil and rock samples (Zhang *et al,* 2021a). Subsequently, in December 2020, the unmanned lunar probe Chang'e 5 landed in Inner Mongolia, carrying a capsule containing lunar soil collected from the lunar surface, thus making China the third country to bring lunar soil to Earth, following the United States and the former Soviet Union (Zhang *et al,* 2021b).

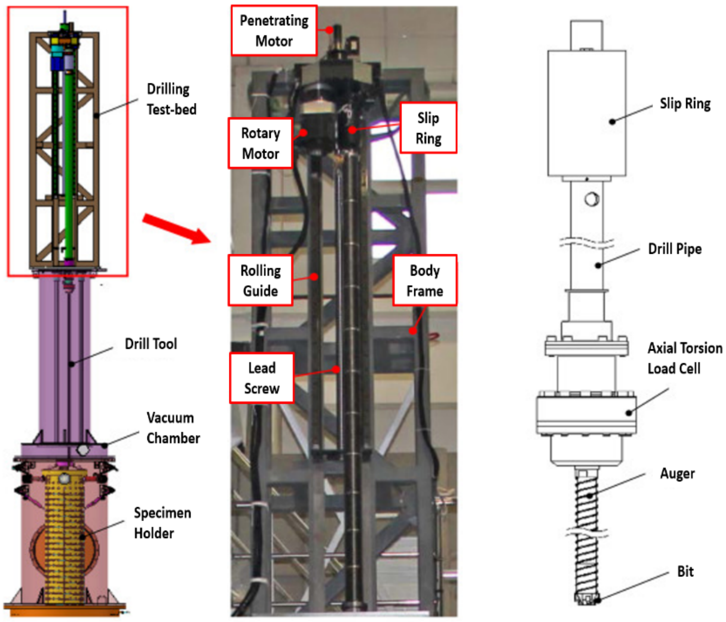


FIG 2 – CAST Schematic diagram of the drilling test-bed (Zhang and Ding, 2017).

Reflecting this global momentum, South Korea is also developing an unmanned drilling rig capable of sampling ice buried up to 1 metre below the lunar surface and analysing stratigraphy. This paper introduces a technique for evaluating ground strength using drilling rigs and drilling information, including reaction force, torque, and drilling velocity, developed thus far.

The world's major spacefaring nations are engaged in a race to develop drilling rigs suitable for space environments to explore and utilise space resources. More recently, research has expanded to encompass drilling and excavation equipment for collecting planetary soil samples, heralding a new era for human missions aimed at sampling planetary soil. In this context, South Korea initiated the development of a drilling rig for space resource exploration in 2016 as a late entrant and is currently in the process of developing a drilling rig prototype and conducting various extreme environment performance tests.

A ground investigation drilling rig typically comprises a body frame, a drive unit, and a rotary unit. The body frame provides structural support, while the drive unit, powered by a vertical motor and gearbox, controls vertical feed. The rotary unit consists of a bit auger rotary motor, bit auger connection, and gearbox for rotational speed control. An auger facilitates cutting, transportation, and sampling functions, with a bit serving as a cutter installed at the end of the auger.

The drilling rig depicted in Figure 3 is distinguished by an integrated load cell capable of measuring reaction force and torque simultaneously. Additionally, drilling speed can be estimated by the rotation speed of the vertical motor, which moves along the timing belt to maintain the vertical transfer and verticality of the drilling rig.

It is equipped with a precision-controlled, encoder-coupled, planetary reduction DC induction motor with an output of 48.6 Watts for rotating the auger, with a reducer gear ratio of 1:230. The output shaft of the motor is connected to the reduction gear, drive shaft, torque metre, drill bit clamp, and drill bit successively. The motor, powered by 24 V of power, with a rated current of 2850 A and a rated rotational speed of 3550 rev/min, operates at a constant speed under rated load to conduct drilling operations.

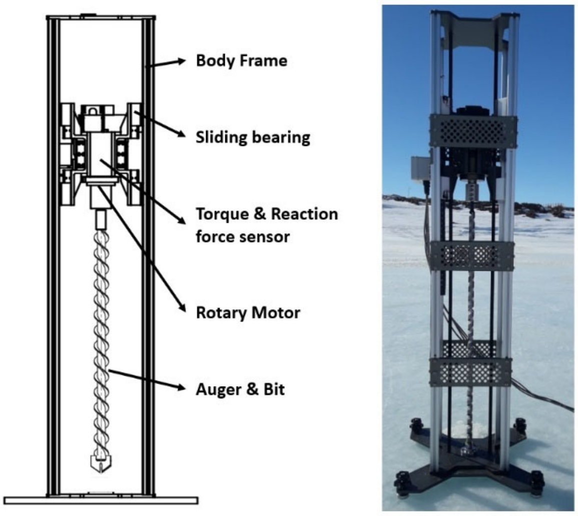


FIG 3 – Planetary ground drilling system

An auger is a relatively simple tool for drilling holes in the soil, comprising variously shaped bits attached to the end of a rotating rod that penetrates the soil, extracting dug soil to the surface. For this experiment, a mechanical auger method employing a two-row screw with a machine auger was utilised. The auger, CNC turned from a round steel bar, boasts a diameter of 22 mm, a helix angle of 32.21°, and a groove depth of 6 mm, as depicted in Figure 4.

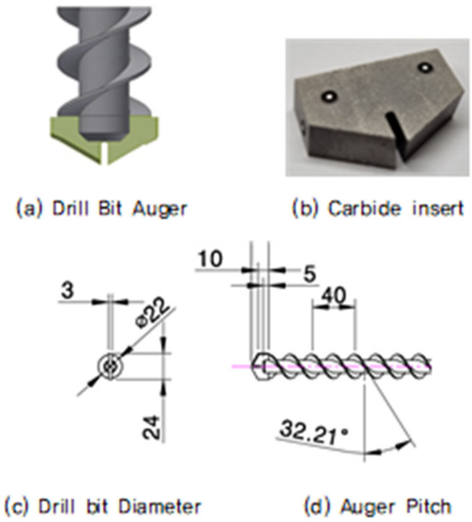


FIG 4 – Design and development of bit auger.

CREATING AN EXPERIMENTAL SPECIMEN

Experimental specimens were fabricated by blending Korea Lunar Simulant-1 (KLS-1), a Korean artificial lunar soil with a particle size distribution and physical and chemical properties akin to lunar soil, with gypsum. The artificial lunar soil primarily comprises loose fine-grained particles with a diameter of less than 1 cm and a specific gravity of 2.94, with the fine-grained content (<0.075 mm) constituting 48.92 per cent.

To achieve varied uniaxial compressive strengths, mix ratios of artificial lunar soil and gypsum were set at 5:5, 6:4, 8:2, and 9:1. After an incubation period of 28 days, experiments were conducted to determine the maximum strength of the specimens.

The specimens measured 250(W) × 250(L) × 500(H) mm, and strength assessment was carried out by coring samples for Unconfined Compressive Strength (UCS), with a diameter of 5 cm and a height of 10 cm, using a sampling rig. To ensure uniform strength distribution, the strength of the specimens utilised in drilling was validated through an indoor experiment.

The unconfined compressive strength varied according to the weight ratio of gypsum and lunar soil, measuring 2.32, 3.54, 5.56, and 6.57 MPa at weight ratios of 50 per cent, 60 per cent, 80 per cent, and 90 per cent gypsum, respectively.

To pilot the developed experimental device, ice cube samples were created using distilled water. These ice samples were produced in a freezing chamber (-15°C, ±0.5°C) using a cuboidal mold measuring 500 mm across, 250 mm long, and 1000 mm high. Freezing was conducted from bottom to top, employing cold plates to maintain a constant sub-zero temperature at the base of a specially designed insulated box. Temperature measurements were taken at various sample heights during the fabrication process, determining that a minimum of 24 hrs was necessary for temperature convergence. The extracted ice samples were packaged to prevent sublimation and stored in a freezing chamber at -15°C for two days to complete the preparation process.

The strength measurements of ice samples were conducted in accordance with ASTMD5520, Uniaxial Compressive Strength Test. The uniaxial compressive strength tester was kept in a freezing chamber to match the sample temperature, and the load reload rate was set to 1 mm/min as per ASTM recommendations. For the test, a 0.8 mm membrane was placed on the top and bottom of the ice sample, with the top and bottom plates of the tester in contact.

Drilling rigs intended for space environments necessitate adept design and fabrication skills to function in extreme conditions while boasting features such as lightweight, miniaturisation, and low power consumption. The UCS results for ice at -15°C revealed that stress in the ice increased nearly linearly, reaching a maximum strength of 4.74 MPa at a strain of approximately 1.5 per cent. The fracture morphology displayed brittle fracture behaviour resembling solid rock. Vertical fracture planar fracture was observed as the primary fracture type, with split fracture occurring due to ice flaking.

GROUND STRENGTH ASSESSMENT TECHNIQUES

To assess ground strength based on drilling data from the drill rig, the correlation between the drilling energy of the rig and the uniaxial compressive strength was analysed. Mechanical Specific Energy (MSE) represents the energy necessary to drill into the ground, aiming to minimise MSE while maximising the Rate of Penetration (ROP) for optimal drilling efficiency. The concept of MSE was initially introduced by Teale (1965) as the energy expended per unit volume of rock cut. Subsequently, Pessier and Fear (1992) expanded on MSE and applied it to the oil and gas drilling sector, where it became widely utilised for assessing drillers' performance. MSE serves to comprehend the drilling mechanism, diagnose efficient drilling operations, assess the cutting ability of the bit due to wear, and evaluate drilling performance in real-time (Curry *et al,* 2005; Dupriest, Mobil and Koederitz, 2005; Caicedo, Calhoun and Ewy, 2005).

To regulate MSE, which signifies drilling rig efficiency, variables such as the weight on the bit (WOB), torque (T), rotational torque, depth of penetration per minute (ROP), and rotations per minute (rev/min) of the drill bit can be controlled. MSE is defined as the ratio of the energy required for ground excavation to the volume drilled, as depicted in Equation 1.

$$\mathrm{MSE} = \frac{Total\ Energy\ Input}{Volume\ Removed} \tag{1}$$

The volume of a drilling borehole is determined by multiplying the cross-sectional area by the depth of penetration, while energy is calculated as the product of the applied load and the distance. The MSE is then divided by the two forces acting on the drilling—the axial force and the rotational force—using the equation. This relationship can be represented as shown in Equation 2.

$$\mathrm{MSE} = \frac{Total\ Energy\ Input}{Volume\ Removed} + \frac{Rotational\ Energy\ Input}{Volume\ Removed} \tag{2}$$

The distance covered by a bit within a specific time interval (△h) can be determined by dividing the penetration rate per hour by the rotation rate per hour. This relationship can be denoted as shown in Equation 3, referred to as penetration per rotation.

$$\Delta \mathrm{h} = \frac{Penetration\ per\ minute}{RPM} = \frac{ROP}{RPM} = P \tag{3}$$

As such, the mechanical specific energy (MSE) is calculated from Equation It can be represented as in Equation 4.

$$\text{MSE} = \frac{WOB}{Area} + \frac{Torque \times 2\pi}{Area \times P} \quad (4)$$

where:

MSE	= Mechanical Specific Energy (MJ/m^3)
WOB	= Weight On Bit (N)
RPM	= Rotations Per Minute
Torque	= Rotational torque (N.m)
Area	= Cross-sectional area of bit (m^2)
ROP	= Rate of Penetration (m/min)
P	= Penetration Per Revolution (m)

Generally, the parameters utilised to compute the MSE are interrelated, and the ideal bit can be determined by minimising the MSE. Historically, achieving the optimal bit has relied on empirical methods rather than theoretical approaches, drawing from experimental outcomes involving different bit types to minimise the MSE. This study aims to examine the relationship between MSE and the uniaxial compressive strength of the ground rather than identifying the optimal bit.

EXPERIMENTAL CONDITIONS AND RESULTS

Drilling experiments involve the rotation of the drill bit to excavate and cut through the centre of the formation. As the cutting progresses from the leading edge of the drill bit, the thrust, known as Weight On Bit (WOB), is set to 100 N to minimise bit wear and achieve optimal cutting efficiency. To calculate and apply the drilling speed during the drilling process and assess the motor efficiency of the drilling rig, the rotation speed of the drilling rig was fixed at 100 rot/min (Rotations Per Minute).

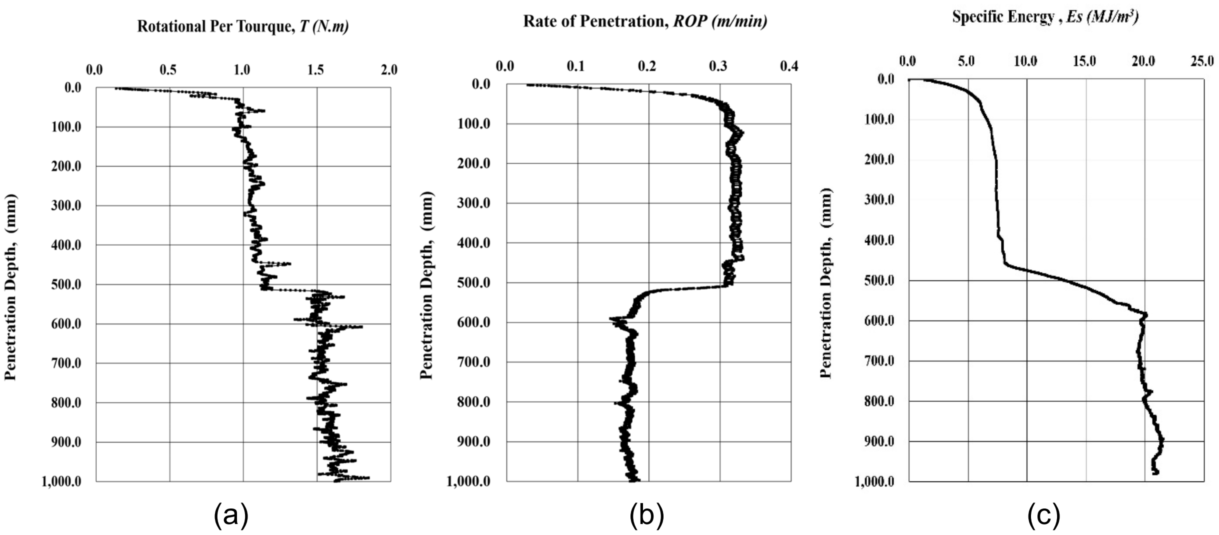


FIG 5 – Measured Data from Drilling 1000 mm of Specimen (Layer #1-Gypsum:Simulant = 50:50) (Layer #2-Gypsum:Simulant = 90:10): (a) Rotational torque, T (N.m); (b) Rate of Penetration, ROP (m/min); (c) Specific Energy, Es (MJ/m^3).

After completing the core sampling, specimens were stacked in four different weight ratios to verify the performance of the drilling rig, and drilling information was measured while drilling to a depth of 1000 mm (500 mm/sample) under constant loading conditions. Figure 6 presents drilling information for two layers of gypsum and artificial lunar soil. Table 1 shows the average values of drilling parameters by drilling depth: rotational torque (T), depth drilled per minute (ROP), rate of penetration

(ROP), and mechanical specific energy (MSE) required to excavate the ground as two formations are drilled.

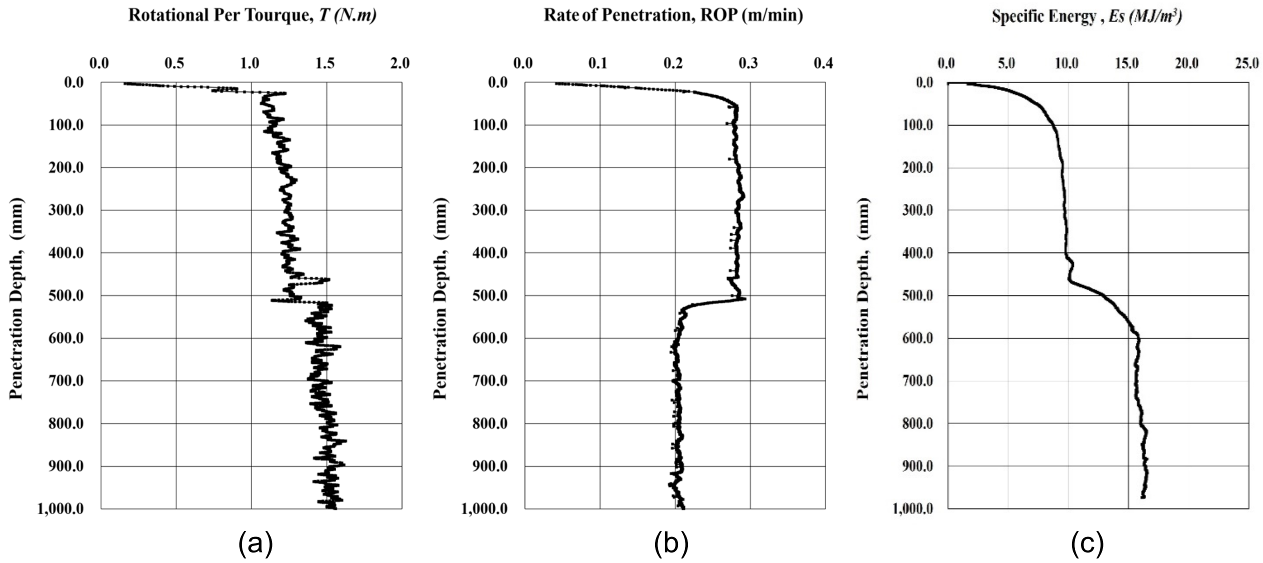


FIG 6 – Measured Data from Drilling 1000 mm of Specimen (Layer #1-Gypsum: Simulant = 60:40) (Layer #2-Gypsum: Simulant = 80:20): (a) Rotational torque, T(N.m); (b) Rate of Penetration, ROP(m/min); (c) Specific Energy, Es(MJ/m^3).

During drilling, the ground resists the drilling force of the bit and the drilling soil of the auger. Particularly, the strength characteristics of the ground resisting the drilling force are proportional to the torque applied to the drilling motor and inversely proportional to the drilling speed. Based on the drilling information, the energy used for drilling was calculated. Primarily, torque is found to be the most influential factor, indicating constant drilling rig efficiency without any increase in cutting torque due to friction resistance during the drilling of a sample with constant compressive strength. The trend of torque with depth was also observed to be effective for stratigraphic analysis, as a sharp change could be observed at the interface of two different specimens (~500 mm).

Drilling information for a 1000 mm ice cube prepared in a cryogenic laboratory at -15°C shows a uniaxial compressive strength of 4.742 MPa, a torque T of 0.775 N.m as the average value of the drilling parameters, a drilling depth ROP of 0.107 m/min, and an energy MSE for excavating the ground of 13.250 MJ/m^3. This is due to the frictional resistance created by the friction surface between the auger and the ground as the drill bit penetrates. The result of calculating MSE by depth based on drilling information shows a similar trend to the torque.

Figure 7 shows the correlation analysis results between observed mechanical specific energy (MSE) and unconfined compressive strength (UCS) based on drilling information. The relationship between UCS and MSE indicates the efficiency of drilling, with drilling generally considered to be 30 per cent efficient. The optimal efficiency of the drilling rig performed in this study was found to be about 34.44 per cent as a result of the experiments.

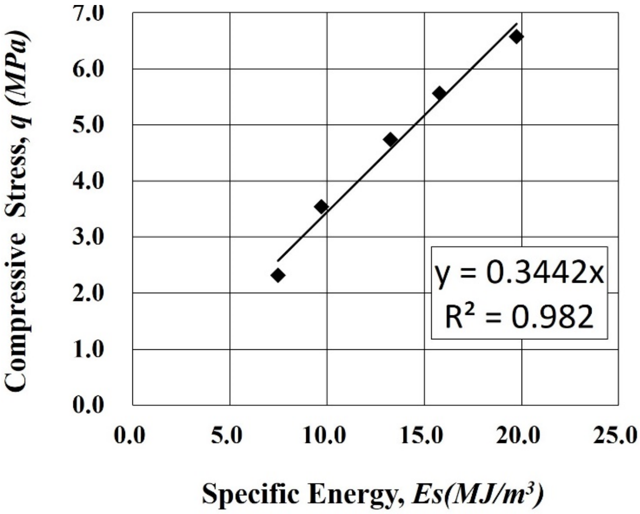


FIG 7 – Proportional relation exists between the drilling specific energy and UCS.

In the case of mixed samples of ice and lunar soil, variations in material properties exist among the constituents. This study aims to analyse the strength and energy correlation for various samples to ensure the reliability of the estimation technique.

CONCLUSIONS

This study introduces a newly developed geotechnical investigation drilling rig designed for celestial bodies. Through experimental analysis of ground strength based on drilling information, the following conclusions have been drawn:

- Indoor experiments were performed to validate the evaluation technique for predicting the uniaxial compressive strength of the ground using the energy consumed by the drilling rig. Among the measurable drilling information, torque exhibited a variation similar to that of the uniaxial compressive strength.
- The drilling speed and torque values remained constant without any fluctuation in vertical load while drilling the same ground, confirming the validity of introducing the energy concept to assess the mechanical properties of the ground.
- Stratigraphy can be distinctly delineated through the torque of the drilling rig, with the potential for analysis through drilling speed. Torque serves as a robust estimator of ground strength, and the energy derived from it can effectively gauge ground strength.
- Based on the outcomes of this study, further experiments are warranted in extreme environments characterised by high vacuum and ultra-low temperatures to ascertain correlations for future planetary ground drilling in space.

ACKNOWLEDGEMENTS

Research for this paper was carried out under the KICT Research Program (project no. 20240247–001, 2024 Dirty Thermal Vacuum Chamber (DTVC) Utilization) funded by Hanwhassystem.

REFERENCES

Caicedo, H, Calhoun, W and Ewy, R, 2005. Unique ROP predictor using bit specific coefficient of sliding friction and mechanical efficiency as a function of confined compressive strength impacts drilling performance, in *Proceedings of the 2005 SPE/IADC Drilling Conference*, pp 117–125.

Curry, D, Fear, M, Govzitch, A and Aghazada, L, 2005. Technical Limit Specific Energy-An Index to Facilitate Drilling Performance Evaluation, in *Proceedings of the 2005 SPE/IADC Drilling Conference*, pp 23–25.

Dupriest, F E, Mobil, E L and Koederitz, W, 2005. Maximizing drill rates with real-time surveillance of mechanical specific energy, in *Proceedings of the 2005 SPE/IADC Drilling Conference*, pp 217–225.

Ju, G H, 2016. Development Status of Domestic and Overseas Space Exploration and Associated Technology, *Journal of the Korean Society for Aeronautical and Space Sciences*, 44(8):741–757.

Pessier, R C and Fear, M J, 1992. Quantifying common drilling problems with mechanical specific energy and a bit-specific coefficient of sliding friction, *Annual Technical Conference and Exhibition*, pp 4–7.

Teale, R, 1965. The Concept of Specific Energy in Rock Drilling, *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, 2(1):57–73.

Thomson, B J, Bridges, N T, Cohen, J, Hurowitz, J A, Lennon, A, Paulsen, G and Zacny, K, 2013. Estimating rock compressive strength from Rock Abrasion Tool (RAT) grinds, *Journal of Geophysical Research*, 118:1233–1244.

Zacny, K, Paulsen, G, Szczesiak, M, Craft, J, Chu, P, McKay, C, Glass, B, Davila, A, Marinova, M, Pollard, W and Jackson, W, 2012. LunarVader: Testing of a 1 meter lunar drill in a 3.5 meter vacuum chamber and in the Antarctic lunar analog site, *Journal of Aerospace Engineering*, pp 1–9.

Zhang, T and Ding, X, 2017. Drilling forces model for lunar regolith exploration and experimental validation, *Acta Astronautica*, 131:190–203.

Zhang, T, Chao, C, Yao, Z, Xu, K, Zhang, W, Ding, X, Liu, S, Zhao, Z, An, Y, Wang, B, Yu, S, Wang, B and Chen, H, 2021b. The technology of lunar regolith environment construction on Earth, *Acta Astronautica*, 178:216–232.

Zhang, T, Zhang, Y, Xu, K, Ding, X, Wei, H, Chao, C, Wang, B and Wang, B, 2021a. Robotic drilling tests in simulated lunar regolith environment, *Journal of Field Robotics*, 38:1011–1035.

Multiphysics modelling and virtual motion simulation to optimise mining systems in extreme conditions – insights from Mars Science Laboratory (MSL) Curiosity Rover

C Tapia[1,2], S Padekar[3], S Harlikar[4], D Likhachev[5] and D Sapkale[6]

1. Adjunct Associate Professor, School of Minerals and Energy Resources Engineering – UNSW, Sydney NSW 2032. Email: carlos.tapia@unsw.edu.au
2. Technical Mining Manager, Dassault Systemes – GEOVIA, Brisbane Qld 4000. Email: carlos.tapia@3ds.com
3. Software Engineering Senior Manager, Dassault Systemes – R&D CATIA, 3DS Pune Campus – Pune, Maharashtra 411057, India. Email: satish.padekar@3ds.com
4. Industry Process Consultant Manager, Dassault Systemes – SIMULIA Multi-body System, 3DS Pune Campus – Pune, Maharashtra 411057, India. Email: salil.harlikar@3ds.com
5. Industry Process Consultant, Dassault Systemes – SIMULIA Fluids, 3DS Shanghai Foxconn, Shanghai Shi 200121, China. Email: dmitriy.likhachev@3ds.com
6. Motion Quality Engineering Specialist, Dassault Systemes – SIMULIA R&D, 3DS Pune Campus – Pune, Maharashtra 411057, India. Email: dhiraj.sapkale@3ds.com

ABSTRACT

In the quest to access valuable critical minerals, humankind is expanding the frontier into extreme environments like space and deep-sea mining. These ambitious enterprises involve considerable costs and lengthy development cycles to ensure the robustness of mining systems in the face of the harshest conditions and unforeseen challenges. Unfortunately, obtaining information from these unexplored territories is complicated. Data is often scarce, incomplete or impossible to obtain until equipment is deployed, leaving engineers facing many uncertainties throughout the design, testing, production and preparation of such missions. Despite these challenges, these extreme environments operate under consistent physical and chemical principles that can be faithfully digitally replicated. However, unexplored areas and dynamic systems like weather and geology continue to carry uncertainties. While eliminating uncertainties remains elusive, Digital Twins offers a means of robust risk management tool. These virtual replicas can excel in simulating extreme conditions and unexpected events, helping optimise and validate mining system designs tailored for such hostile environments.

This study takes inspiration from the Mars Science Laboratory (MSL) Curiosity Rover's wheel damage rate to develop a Multiphysics Modelling and Virtual Motion Simulation (MMVMS) system. Using advanced Generative Design, this MMVMS system refines the MSL's design, simulates component and system performance, and assesses the risk of premature damage while operating on Mars. Additionally, MMVMS integrates cutting-edge CAD design technologies from aerospace and manufacturing to realistically recreate the Martian environment and a detailed representation of MSL, allowing mobility verification and validation simulation to test different components in terms of materials, design, weight, power and, therefore, cost. The research highlights the precision of MMVMS in replicating extreme conditions, simulating and evaluating internal and external variables influencing the entire system (Rover) in real-time, and predicting movements, failures, and premature damage. This sophisticated Digital Twin technology, showcased in this research, holds promise not only for space missions but also to be adapted for terrestrial and deep-sea mining operations.

INTRODUCTION

Mineral resources have been fundamental to human development, driving economic growth and sustaining societies for millennia (Tapia Cortez *et al*, 2018). However, as the global demand for resources rises, exploration efforts have expanded beyond conventional boundaries into previously uncharted territories, including extreme environments such as deeper and unconventional deposits, the deep sea, and even space. Current endeavours in planetary exploration, including missions to the Moon, Mars, and asteroids, not only promise to unlock vast reservoirs of valuable minerals but also serve as catalysts for exploring new frontiers and technological innovation. These audacious missions offer invaluable opportunities to understand and assess the uncertain and undiscovered challenges that terrestrial mining in extreme environments could face in the future.

Mining and exploration in extreme environments present multifaceted challenges that demand specialised infrastructure and cutting-edge technologies. Facilities like the NASA Jet Propulsion Laboratory (JPL) testing yard and the Kennedy Space Center (KSC) play critical roles in simulating conditions akin to Martian terrain and lunar surfaces (Griffin, 2020; NASA JPL, 2017; Zhou *et al*, 2014). However, while these facilities excel in replicating specific environmental conditions, such as terrain features or gravitational forces, they encounter limitations in replicating all conditions simultaneously. Complex factors like lower gravity, dust storms, cosmic rays, and other navigational challenges pose significant hurdles that are challenging to simulate comprehensively.

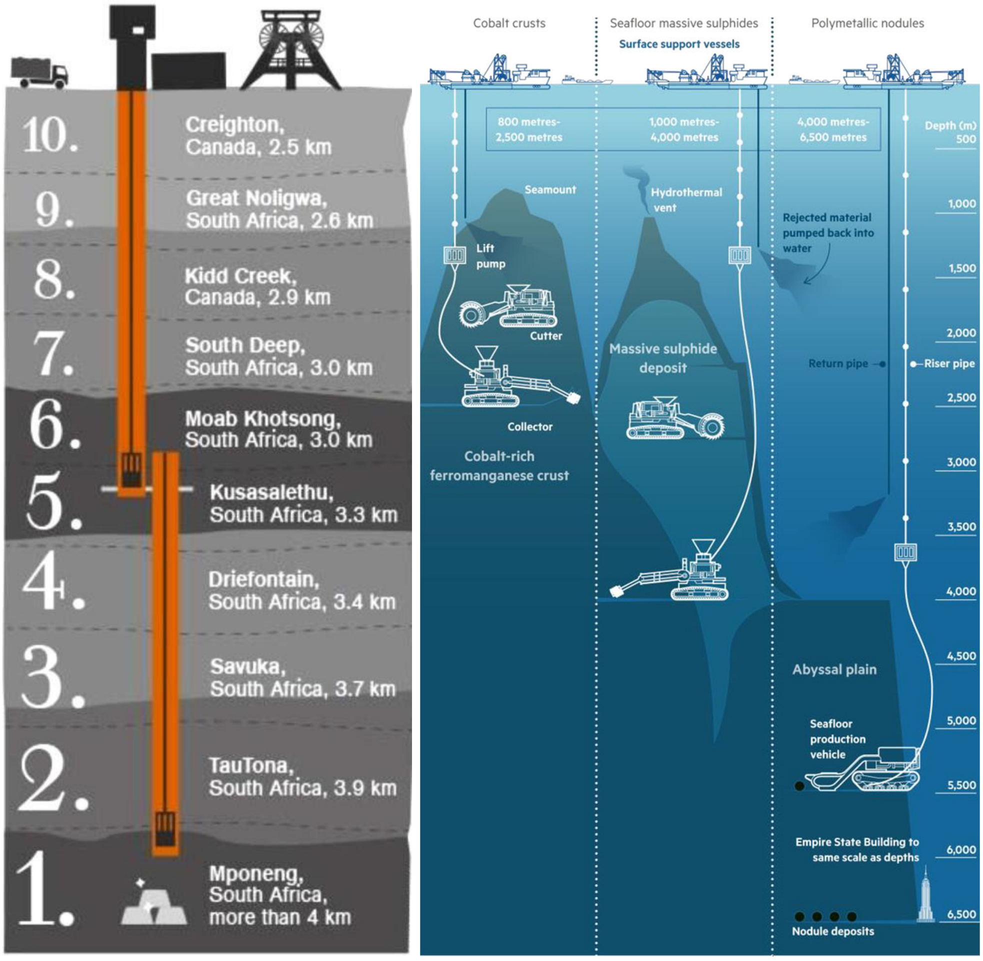
Moreover, despite significant advancements in infrastructure and technology, designing systems for extreme environments remains a daunting task (Pelech *et al*, 2021; Zhou *et al*, 2014). Venturing into extreme environments for mining or exploration purposes on Earth or in space poses a trifecta of challenges: extent, cost, and risk. Planning, designing, and deploying projects in extreme environments are extended processes due to the limited availability of data regarding the physical and environmental conditions. This scarcity often demands a meticulous and continuous iterative process to overcome data limitations and meet technical constraints. Additionally, the iterative nature of these enterprises greatly influences their finance, as the design and testing process incurs significant costs. Despite the long and costly process of designing and testing, the unpredictable nature of unfamiliar extreme environments adds risks that are commonly addressed through redundancy and ruggedisation (Popa-Simil, 2009; Thangavelautham, Chandra and Jensen, 2019; Zacny and Bar-Cohen, 2009). While these measures increase the chances of success, they also come with financial and time-related challenges. The need for duplicate or reinforced components not only raises expenses and weight but also extends (Saydam *et al*, 2015) the duration of development.

Emerging technologies such as digital twins and simulation offer promising avenues for addressing these challenges (Srividhya, Sharma and Kumar, 2013; Zhou *et al*, 2014). By harnessing advanced multiphysics modelling and simulation techniques (Pelech *et al*, 2021) and integrating generative design applications, researchers can optimise complex systems in virtual environments, streamlining the design process and minimising the need for costly physical prototypes. This study underscores the synergistic potential of Generative Design and Multiphysics Simulation in comprehensively integrating all relevant variables to assess the design and behaviour performance of equipment operating under extreme conditions. Using the MSL Curiosity rover as a case study, this research exemplifies virtual simulation's efficacy and financial benefits in expediting research, enhancing technical efficiency, reducing costs and development time, and mitigating risks. Conducted on the 3DEXPERIENCE (3DX) platform of Dassault Systèmes (3DS), employing CATIA for design and rendering, SIMULIA for Multiphysics and generative design simulation, and NETVIBES for analytics, data storage, and collaboration in a cloud-based setting, this comprehensive technological framework underscores the viability of interdisciplinary and multinational collaboration in all stages of projects.

The organisation of this paper is as follows: section 2 delineates the opportunities and challenges of Extreme Mining, focusing on data scarcity and uncertainties. Section 3 reveals the utility of digital twin technologies for enterprise and risk management. Section 4 outlines the Multiphysics Modelling and Virtual Motion Simulation (MMVMS) system. Section 5 presents the case study of MSL. Finally, Section 6 presents the main conclusions and recommendations for future research.

EXTREME MINING

The depletion of shallow high-grade ore deposits persists as the demand for mineral commodities, particularly critical minerals, steadily increases (Palaia IV *et al*, 2009). This urges exploration into extreme environments characterised by unpredictable climatic and operational conditions, often situated in remote and unconventional geological settings (Figure 1), presenting numerous uncertainties similar to those encountered in space exploration missions (Fraser, 2009; Thangavelautham, Chandra and Jensen, 2019).



(a) (b)

FIG 1 – Extreme mining environment: (a) the ten deepest mines of the world (Dräger, 2024), (b) seabed mining options (Bryan and Dempsey, 2023).

New mining ventures face inherent uncertainties from unconventional deposits and unpredictable extreme conditions, such as temperature, pressure, and accessibility. Data in unexplored territories is typically scarce and often inferred indirectly through aggregation and interpolation (Do *et al*, 2014; Pelech *et al*, 2021). Obtaining reliable data in remote and unexplored mining locales is vital for evaluating the feasibility of mining endeavours and developing and deploying specialised equipment capable of operating effectively and reliably under harsh conditions (Pelech *et al*, 2021; Zacny and Bar-Cohen, 2009).

Addressing data scarcity in remote-unexplored regions requires a multifaceted approach (Pelech *et al*, 2021), leveraging advanced techniques such as remote sensing technologies and unmanned aerial vehicles (UAVs) to overcome logistical challenges and expand exploration efforts. However, these technologies encounter technical constraints, primarily related to weight and susceptibility to environmental stresses. Supplementary methods like the Internet of Things (IoT) may help bridge some gaps but also present limitations, including infrastructure aging and sensor unreliability due to exposure to severe environments, resulting in incomplete data (Gao *et al*, 2023; Thangavelautham, Chandra and Jensen, 2019). *In situ* data collection through exploration campaigns remains the primary avenue for informed decision-making and risk management; consequently, specialised equipment with high reliability and endurance is needed. Due to the unfeasibility of deploying humans to these sites, these equipment should be equipped with sensitive automation or remote control technologies, which requires heavy ruggedisation (Thangavelautham, Chandra and Jensen, 2019; Zacny and Bar-Cohen, 2009). However, as budgetary constraints and time limitations stall the development and deployment of such equipment, a delicate balance between technical feasibility and financial viability is imperative.

Challenges encountered in extreme mining settings parallel those encountered in space exploration programs, particularly on Mars (Zacny and Bar-Cohen, 2009). Missions like the Viking, Mars Pathfinder, Mars Science Laboratory (MSL – Curiosity), and Perseverance rovers, and others (Figure 2), navigate uncertain and unexplored terrain using limited and incomplete data (Miley, Yang and Rice, 2009). Robust yet lightweight machines equipped to capture as much information as possible have been instrumental in ensuring mission success by carefully balancing design, functionality, weight, and redundancy (Popa-Simil, 2009; Zacny and Bar-Cohen, 2009). Despite the significant costs involved, this approach has been crucial in navigating uncertainties and mitigating potential failures (Do *et al*, 2014; Rapp and Rapp, 2016). The costs associated with developing and deploying reliable and enduring equipment are not exclusive to space exploration but are also prevalent in deep-sea and deep-mining ventures on Earth. Nonetheless, budgetary constraints and funding fluctuations remain, indirectly influencing effective risk management strategies encompassing data collection efforts and decision-making processes.

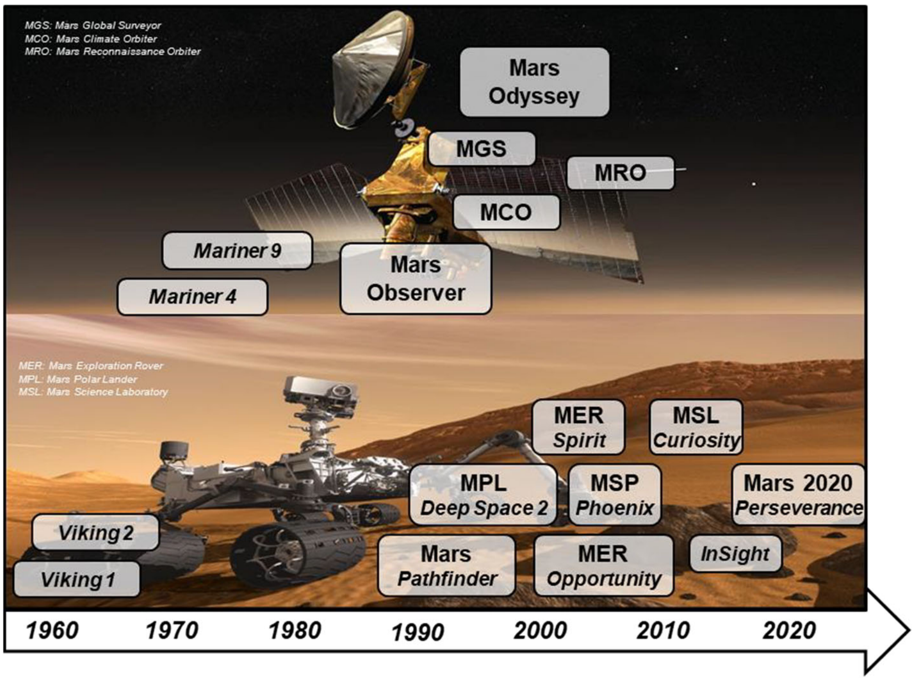
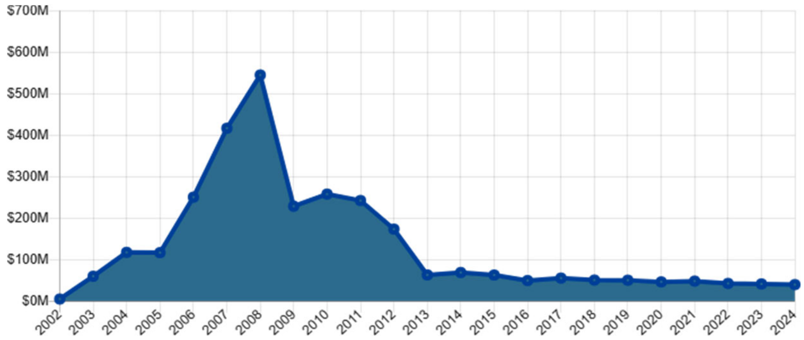


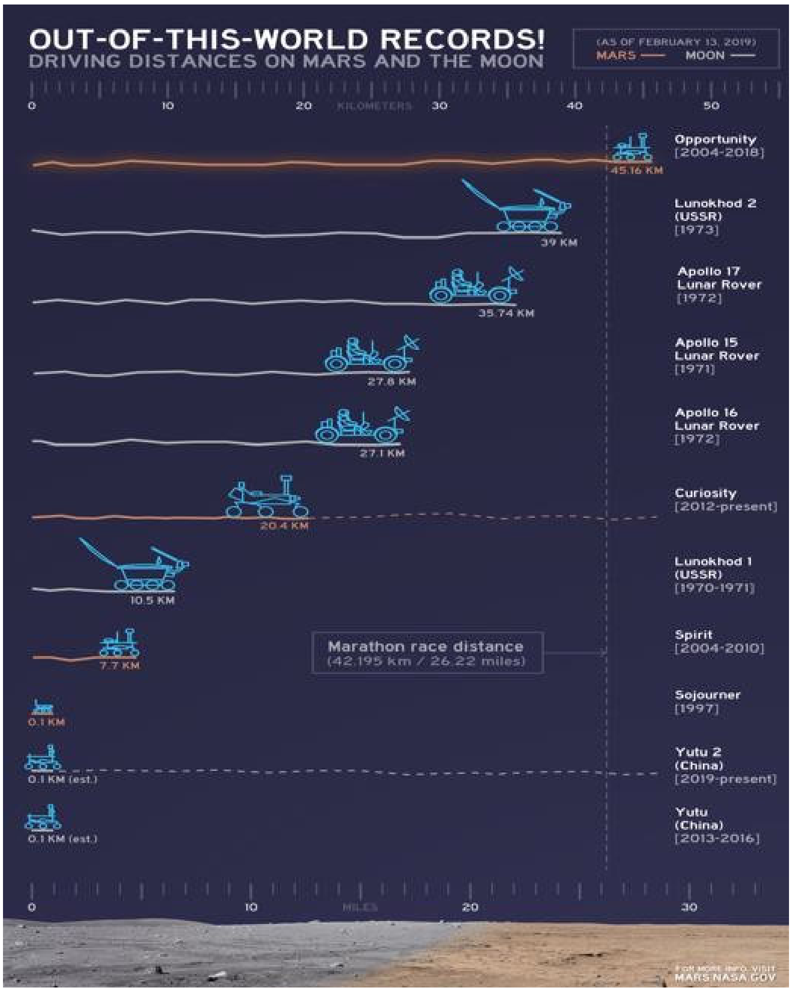
FIG 2 – NASA Mars exploration evolution.

The Mars Science Laboratory (MSL) project, with a development cost of approximately $2.53 billion over ten years, exemplifies the trade-off between cost and endurance in extreme environments (Figure 3a) (The Planetary Society, 2024). Equipped with redundancy, MSL faced challenges such as connectivity loss only eight months after landing on the Martian surface. In March 2013, one of its two onboard computers became corrupted and failed to turn off and enter 'sleep mode' as planned. Its rugged design facilitated continued operation (Kaufman, 2013) (NASA MSL) and exceeded expectations by traversing more than 19 km on the Martian Surface (Figure 3b). However, the endurance of MSL may have been overestimated, as it was originally designed for a two-year operational span, underscoring the need for careful consideration of cost-benefit trade-offs.

Although sophisticated equipment can carry advanced instruments for data capture, there remains an inherent risk of reliability issues due to unforeseen failures or environmental damage. This risk, coupled with the intrinsic uncertainties of geological characteristics such as ore grades, mineral distributions, structural settings, and continuity, complicates resource assessment and mission planning (Ho *et al*, 2014; Pelech *et al*, 2021; Zacny and Bar-Cohen, 2009).



(a)



(b)

FIG 3 – MSL facts: (a) Costs per fiscal year (USD current price) (The Planetary Society, 2024), (b) Comparisons among the distances driven by various wheeled vehicles on the surface of Earth's Moon and Mars, as of February 13, 2019 (NASA, 2019).

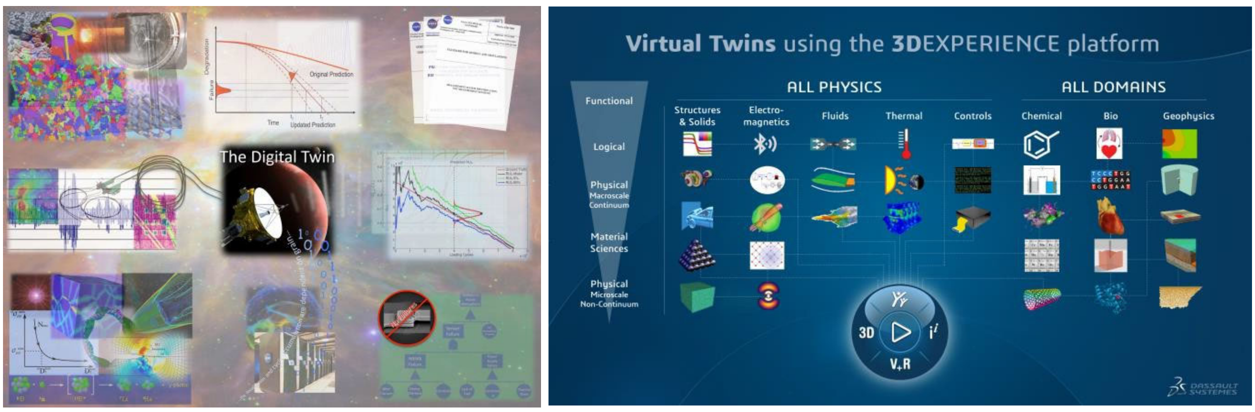
New technologies and techniques are aiding in managing risks and uncertainties by modelling with uncertainties (Ho *et al*, 2014). These proactive risk management frameworks, including scenario analysis and contingency planning, empower organisations to anticipate and mitigate potential risks. The integration of geological modelling, engineering design, and simulation tools enables stakeholders to quantify and analyse uncertainties associated with resource estimation, mission planning, budgeting, and design, facilitating the assessment of a wealth of data that can be easily created, updated, and improved (Do *et al*, 2014; Pelech *et al*, 2021; Thangavelautham, Chandra and Jensen, 2019).

DIGITAL TWINS

A digital twin is a virtual representation of a physical asset, such as a product, platform, or ecosystem, that integrates multiphysics, multiscale, and probabilistic simulations. It mirrors the real-world entity's characteristics and functionalities throughout its life cycle, incorporating data from various sources. Digital twins can extend to products, platforms, or even complex ecosystems like cities and planets. These digital representations are continuously updated and visualised to predict current and future conditions in both design and operational environments. By leveraging integrated simulations and service data, digital twins enhance decision-making processes by providing insights into potential challenges and opportunities. This approach enables the retrieval of relevant digital data to address any occurring challenges through simulation or optimisation functions, ultimately enhancing the resilience and performance of the physical asset (Botín-Sanabria *et al*, 2022; Erkoyuncu, Butala and Roy, 2018; Glaessgen and Stargel, 2012; Shafto *et al*, 2010; Talkhestani *et al*, 2018).

Virtual twins, empowered by high-fidelity modelling and simulation and advanced computing, offer numerous benefits. These include fostering creativity through experimentation and what-if analysis, providing insights into constraints and causality, enabling large-scale data analysis and integration for scientific discoveries. Moreover, they support training, simplify operations, facilitate early testing of complex systems, ensure high-reliability real-time control, optimise mission design, reduce risks, shorten mission design-cycle time, and lower life cycle costs (Botín-Sanabria *et al*, 2022; Shafto *et al*, 2010). Additionally, Digital Twins promise cost reduction, risk mitigation, enhanced efficiency, service improvements, bolstered security, reliability, resilience, and informed decision-making. Ultimately, they increase operational availability and reduce associated expenses throughout the asset's lifespan (Van Der Horn and Mahadevan, 2021).

Developing Digital Twins confronts formidable challenges, especially as models span multiple domains. Integrating diverse engineering models into a unified Digital Twin and synchronising real-world changes pose significant hurdles. Currently, there is no optimised method to seamlessly integrate various engineering models into the Digital Twin system. Additionally, coordinating different perspectives on mechatronic systems adds layers of complexity (Talkhestani *et al*, 2018). A systematic approach to syncing the Digital Twin with the physical system is essential to maintain consistency throughout its life cycle. These challenges underscore the critical need for innovative synchronisation strategies. Similarly, in space exploration, accurately modelling complex systems is vital to ensure mission safety due to their high costs and unique characteristics (Shafto *et al*, 2010; Talkhestani *et al*, 2018). Figure 4 depicts the high level components of a Digital twin and how should multiphysics, synchronisation and integration are practically addressed by the Multiphysics Modelling and Virtual Motion Simulation of 3DS utilised in this research.



(a) (b)

FIG 4 – Digital twin representation – the paradigm of several attributes are incorporated in a single platform (Glaessgen and Stargel, 2012); 3DS Multiphysics Modelling and Virtual Motion Simulation integrated into the 3DX.

MULTIPHYSICS MODELLING AND VIRTUAL MOTION SIMULATION (MMVMS) SYSTEM

Generative design

Generative design employs computational techniques to streamline the design process by swiftly translating given requirements, constraints, uncertainties, and design parameters into viable shapes. Rather than starting from scratch, it begins with predefined specifications, such as available space, applied forces, required materials (eg steel, aluminium, polymer), and boundary conditions. This method simplifies the generation of design concepts based on predetermined criteria. Moreover, depending on the chosen manufacturing process (eg casting, forging, milling, additive manufacturing), generative design enables shape adaptation to suit manufacturing constraints. Topology optimisation, a long-standing subject of academic research and commercial application, is integral to generative design by determining the optimal material distribution for a design under specific usage conditions, aiming to meet structural requirements while minimising mass to reduce weight and conserve material. However, while topology optimisation is tied to a specific algorithmic process, generative design encompasses various computational methods to enhance the design process, emphasising efficiency and adaptability (Khan and Awan, 2018; Krish, 2011; Shea, Aish and Gourtovaia, 2005).

Generative design is now enabling architects to explore thousands of design possibilities within CAD environments. Despite the lack of a clear definition and formal methods for its implementation, its significance is now widely recognised by engineers and researchers (Krish, 2011).

CAD design tools

CAD design tools are instrumental in every stage of generative design, from conceptualisation and design iteration to mechanical analysis and integration of complex subsystems. By leveraging the capabilities of CAD software, engineers and researchers can accelerate innovation, enhance the reliability of terrestrial equipment, and ultimately advance the frontiers of space exploration.

In the context of Mars exploration, the primary way of assessing rovers' designs has been the construction of physical twins and testing them in designed physical terrains. While it has been proven effective, CAD tools can further enhance rovers' design performance by providing a digital twin from early stages that is able to model, display, and test all components. This research used CATIA® in different stages of the project, as listed below and shown in Figure 5:

- An exact geometry rover model was from accurate 3D scans of the actual rover model.
- 3D point cloud data of the Martian surface was created and rendered to accurately represent the Mars terrain, which is fundamental for testing performance under real conditions.
- Engineering connections and excitations for the rover components like cameras and antennas were defined. This step is crucial for movement simulation.

A hierarchical simulation process can significantly augment the effectiveness of generative design when individual (or component) designs are interconnected within the overall system design. These individual designs are automatically executed, allowing for parameter modifications and evaluations within specified ranges of values or combinations. Should one component's design prove suboptimal, parameter adjustments trigger automatic updates to that component and the entire system design.

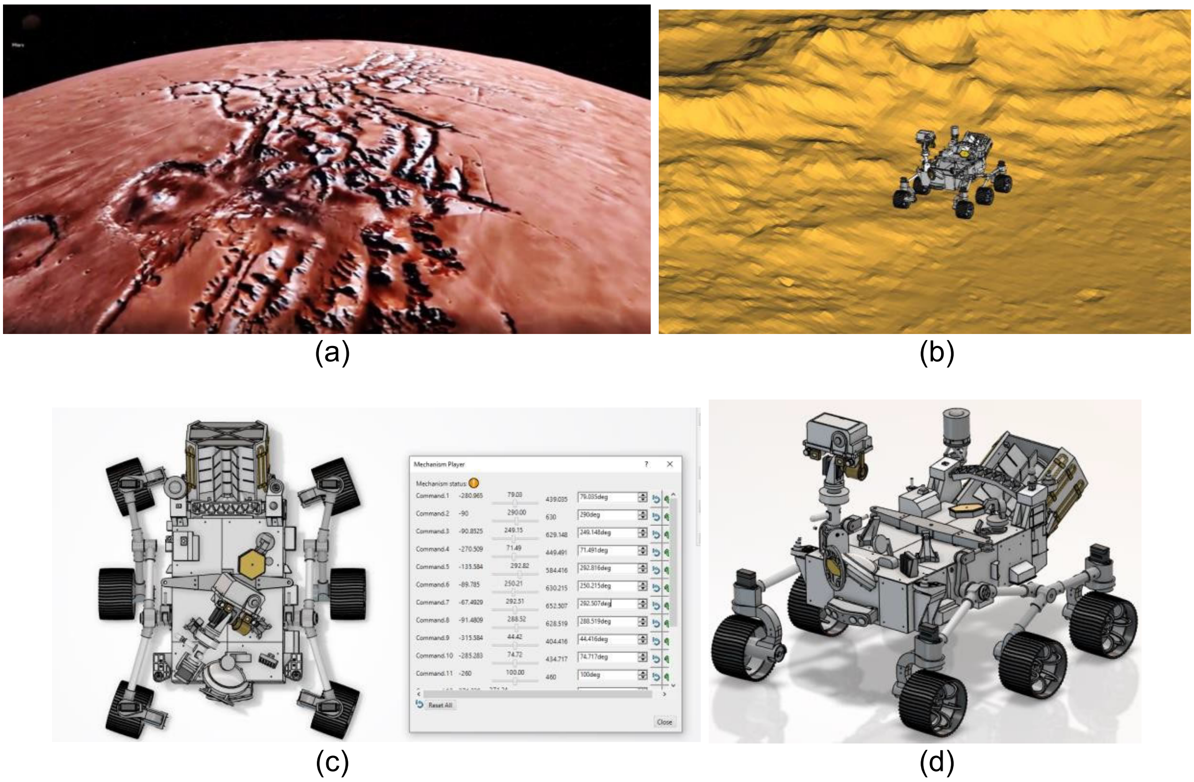


FIG 5 – CAD tools: representing Martian environment and MLS Curiosity Rover: (a) Mars in Planet Studio of Dassault Systemes, (b) Martian terrain rendered and MSL design CATIA®, (c) The four-wheel steering CATIA®, (d) MSL Rover components position CATIA®.

Multiphysics setting – visualisation and testing of environmental and physical conditions

Advanced 3D visualisation techniques are increasingly valuable in understanding complex phenomena like weather and climate simulations, generating vast data sets. Integrating climate models with spatial data enables the identification of correlations and the study of key processes. This advancement is particularly significant when replicating terrain and environmental aspects, as demonstrated in 3D climate simulations of the early Martian climate. Furthermore, landscape visualisations are extensively utilised to assess large-scale projects, simulate landscape changes, and conduct research, underscoring their flexibility and precision in evaluating various scenarios (Forget *et al*, 2013; Helbig *et al*, 2014; Paar, 2006).

Early and comprehensive 3D assessments under actual environmental conditions are essential to ensure the efficiency of new designs in resource-constrained enterprises (Figure 6). The use of science-based realistic simulation, which facilitates the rapid evaluation of new ideas, requires an accurate and precise representation of real physics conditions, including terrain, temperature, wind, and pressure, among many others, to identify optimal trade-offs during the initial design phases while adhering to technical, time and budget constraints. This approach accelerates the design and production stages while ensuring the reliability of equipment by:

- Standardising all engineering subsystems, including all physics affecting each one of the components and the whole system.
- Converging CAD, analysis, and design controls to optimise designs and ensure correctness from the outset rapidly.
- Enabling accurate simulation from early and frequently in the design process to gain insights into key performance metrics.
- Reducing or eliminating physical testing and prototyping through automation of engineering tasks using templates.

- Unifyng modelling and simulation processes to enhance efficiency and coherence throughout the design life cycle.

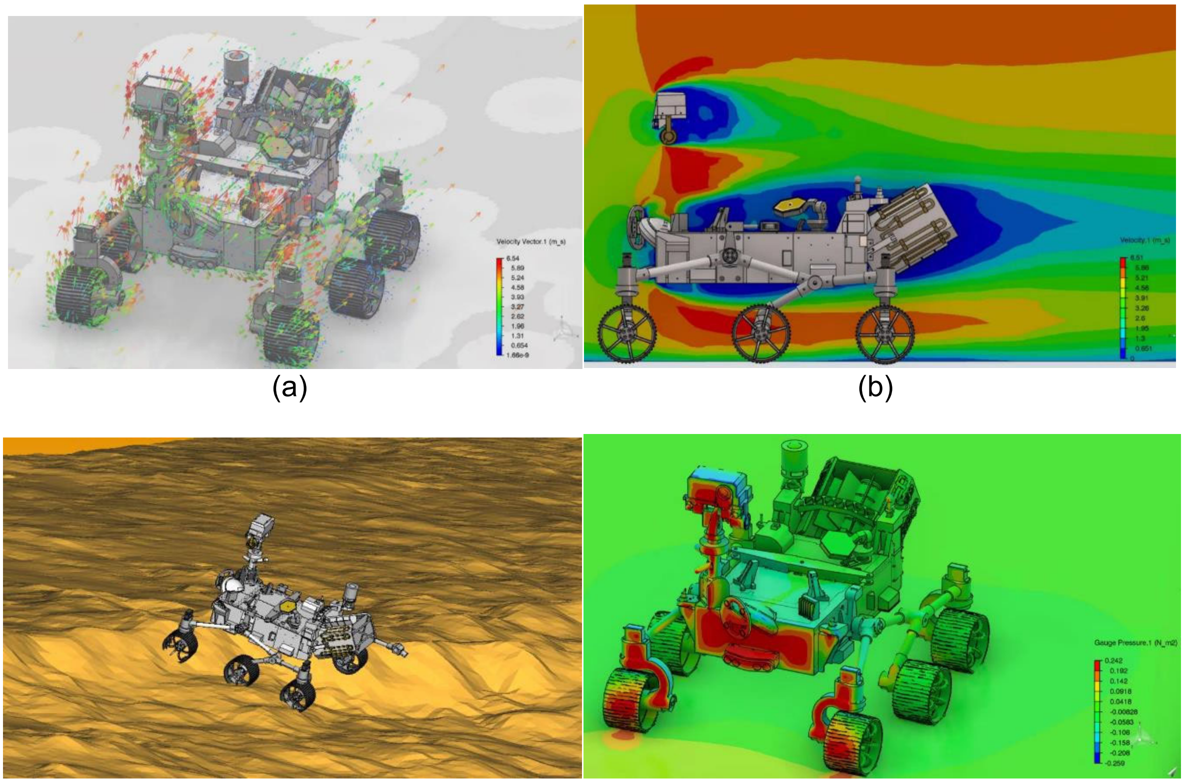
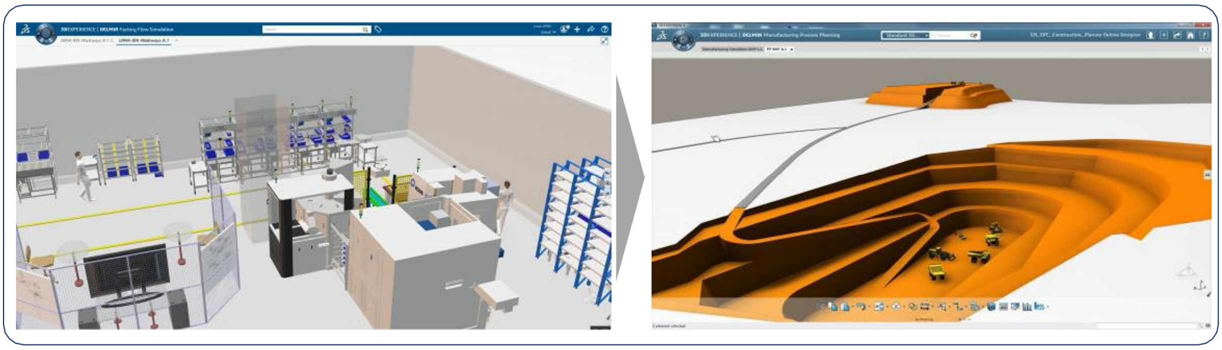


FIG 6 – MSL Curiosity Rover multiphysics simulation and visualisation: (a) Wind forces absolute vectors, (b) Wind forces influence on the design, (c) Terrain and traverse, (d) Pressure effects.

Simulation

The advancement in simulation tools over recent decades has significantly expanded the applicability of simulation as an alternative to systems analysis. This is particularly relevant in the context of quantitatively assessing environmental variables, which entails navigating nonlinear models and characterising interdependent variables, factors, and parameters. For complex systems like equipment and Off-Earth rover design, as the topic of this research, simulation-based problems are often multifaceted, requiring the simultaneous evaluation of various performance criteria. However, this complexity can pose challenges, primarily when multiple simulation models assess different aspects of the problem. In addressing these challenges, hierarchical simulation emerges as a valuable approach. By breaking down complex systems into interconnected components, hierarchical simulation effectively manages the intricacies of simulation models. Defining hierarchical modelling can be ambiguous, potentially complicating its application in simulation modelling. Therefore, establishing a clear framework for hierarchical modelling is essential to ensure its effective implementation (Choudhary, Papalambros and Malkawi, 2005; Luna, 1993; Voit, Balthis and Holser, 1995). Figure 7 shows the practical applications of simulation to solve complex multidimensional systems.



(a)

(b)

FIG 7 – Technology transfer: (a) Discrete event simulations – from manufacturing to mining fleet evaluation, (b) Hierarchical simulation – from automotive to strategic mine planning (Tapia and Hay, 2023).

This research used the SIMULIA® software package to simulate the intricated complexity of design and evaluate MSL's performance under actual Martian conditions. The reasons and benefits for incorporating this tool are:

- Ensure a seamless design between components allows orchestrating a dynamic motion simulation by combining the rover design, terrain and environment.
- This virtual motion simulation facilitated the exploration of wheel-terrain interactions and enabled the refinement of the Rover's wheel and propulsion systems based on the simulations' results.
- Operating under real Martian physics, including the critical gravitational force, to achieve a high-fidelity simulation performance in the Martian terrain.
- Ensure real-time data extraction during simulation, including key metrics such as 'Tire Forces' and 'Dynamic Rover Body Roll' meticulously plotted and analysed.
- Incorporate Computational Fluid Dynamics (CFD) simulation of Martina patterns to assess the effects of wind on the performance of the rover and components' endurance and predict potential points of failure.
- Seamless interaction of multiphysics simulation in a single integrated environment.

Optimising systems in extreme environments – experience from MSL thermal analysis

Thermal analysis is integral to optimising mining systems in extreme conditions like those faced during the MSL mission. It supports managing heat generated and dissipated by spacecraft and rover components (Figure 8a), which is crucial for designing and optimising heat rejection systems (HRS) like the mechanically pumped single-phase fluid (MPFL) loop utilised in MSL (Bhandari and Anderson, 2013). These systems dissipate waste heat from components such as the Multi-Mission

Radioisotope Thermoelectric Generator (MMRTG) while regulating thermal conditions during mission phases like cruise, entry, descent, and landing (EDL) on Mars. The spacecraft encounters varying thermal environments during EDL, from intense heating during atmospheric entry to cold Martian surface temperatures.

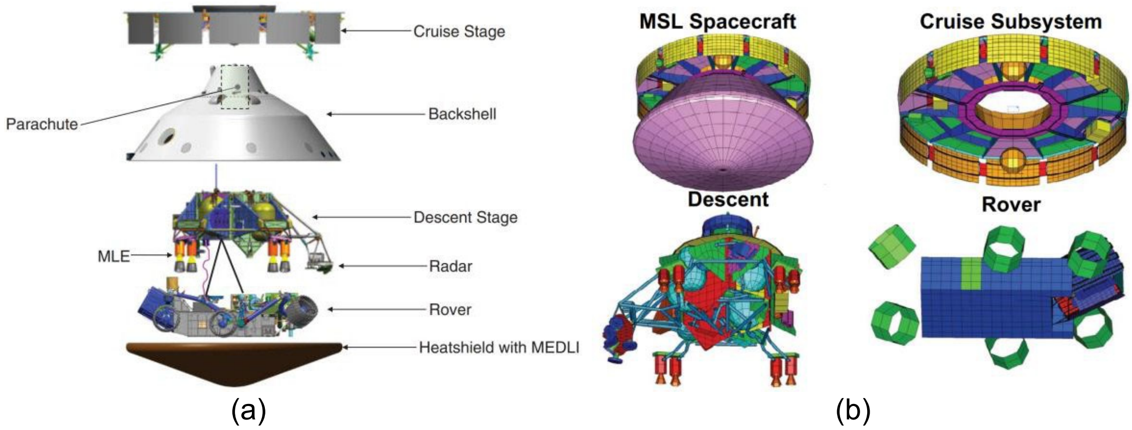
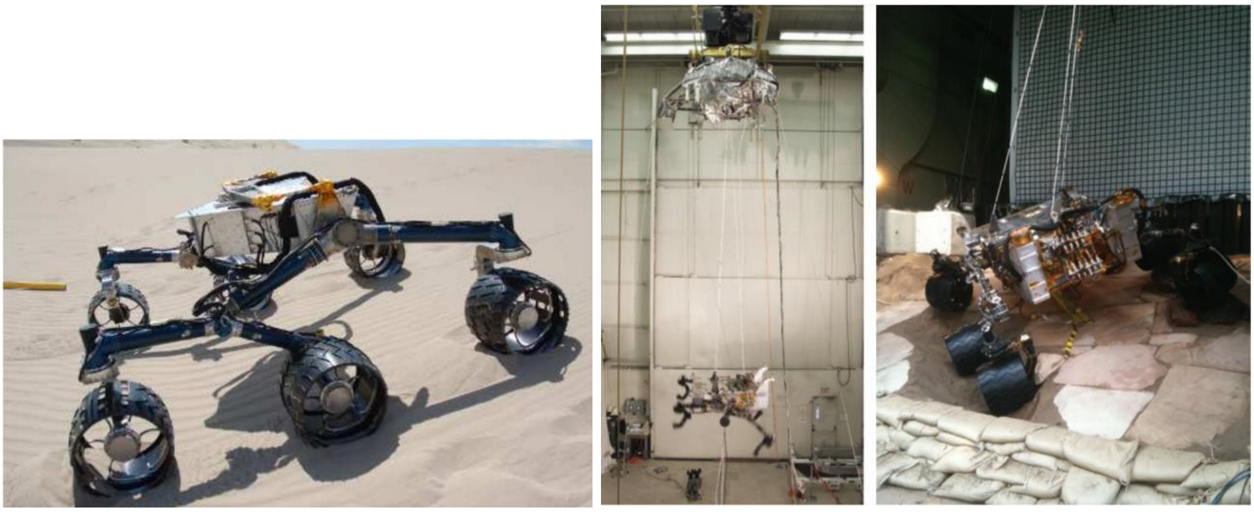


FIG 8 – MSL components: (a) Major elements (Kornfeld, 2014); (b) System level thermal model (Paris, 2008).

In this sense, computational fluid dynamics (CFD) simulations play a key role in predicting fluid temperatures and flow rates within cooling loops, for example, optimising heat transfer efficiency during the mission's cruise phase and descent stage propulsion system (Figure 8b) (Paris, 2008). Despite challenges in accurately modelling complex thermal phenomena (ie representing geometries and validating results against experimental data), CFD simulations provide valuable insights for mission planning and design. These simulations help in understanding heat transfer coefficients, temperature distributions, and heat rejection strategies under Martian environmental conditions, ensuring the selection of the more suitable material and design to ensure a reliable operation and longevity of equipment in challenging environments like Mars or deep-sea mining operations on Earth (Quattrocchi, 2022).

Structural analysis – engineering solutions for exploration

Structural analysis is vital for designing mechanical systems that are able to endure harsh environments like those encountered during space missions. It involves assessing aerodynamic forces, thermal loads, and mechanical stresses to ensure the system's integrity throughout the deployment and operation phases. For instance, the MSL heatshield underwent rigorous analysis to endure atmospheric entry heat, while the parachute design was scrutinised for safe rover deceleration (Sengupta *et al*, 2008). As exemplified by ARTEMIS, computational approaches enable simulations of rover-terrain interactions, which are vital for assessing mobility and durability on Martian surfaces (Figure 9a). This analysis included evaluating forces acting on rover wheels and optimising mobility for diverse terrains (Kornfeld, 2014).



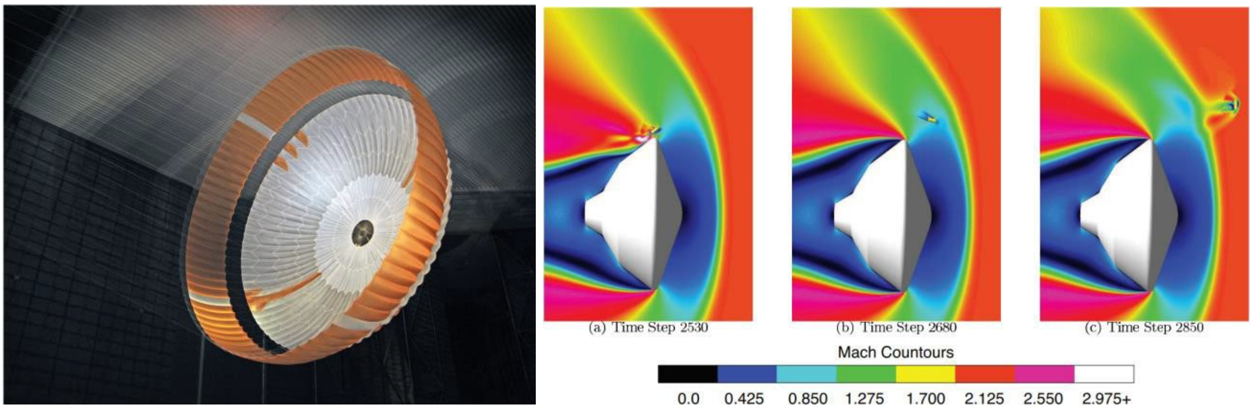
(a) (b) (c)

FIG 9 – Sky crane validation: (a) Scarecrow at the Dumont Dunes site while attempting an upslope drive (Senatore, 2014), (b) Full-motion drop test, (c) touchdown tests (Kornfeld, 2014).

While uncertainties and computational complexity challenges are unavoidable, structural analysis offers predictive capabilities essential for efficient mission planning. Validating multiphysics phenomena by digital experiments presents technical challenges, especially in extreme environments like Mars. Uncertainties in soil properties and environmental conditions necessitate careful calibration of simulation models against experimental data to ensure accuracy (Cameron, 2009; Li, 2013). While simulation tools provide high-fidelity representations of system dynamics, their accuracy depends on underlying assumptions and corrections, highlighting the importance of thorough model validation through physical testing, such as the Sky Crane full-motion drop (Figure 9b). and touch down (Figure 9c) tests (Agarwal, 2021). Nonetheless, ongoing advancements promise more robust and efficient mining operations in space and deep-sea environments facilitated by tailored structural analysis tools.

Fluid analysis

Fluid analysis is primarily used to study how fluids interact with structures and objects, aiming to improve aerodynamics or hydrodynamics and reduce energy consumption. Robust fluid analysis data enhances mission resilience and success rates, enabling timely adjustments based on reliable information in dynamic environments. For example, in the context of the MSL mission, fluid analysis refined parachute deployment models, ensuring safe landings on the Martian surface (Figure 10a) (Cruz, 2013). By simulating aerodynamics, engineers determine critical factors like parachute opening forces and aeroshell dynamics, crucial for mission success. Fluid analysis also helps in understanding spacecraft interactions, ensuring stability and control during descent (Schoenenberger, 2009) using aerodynamic data commonly generated by computational fluid dynamics (CFD) tools like LAURA and OVERFLOW (Figure 10b). However, accurately representing fluid-structure interactions poses challenges, especially during supersonic deployment, as high-fidelity simulation demands advanced (CFD) techniques and resources that might be planned prior to starting any simulation.



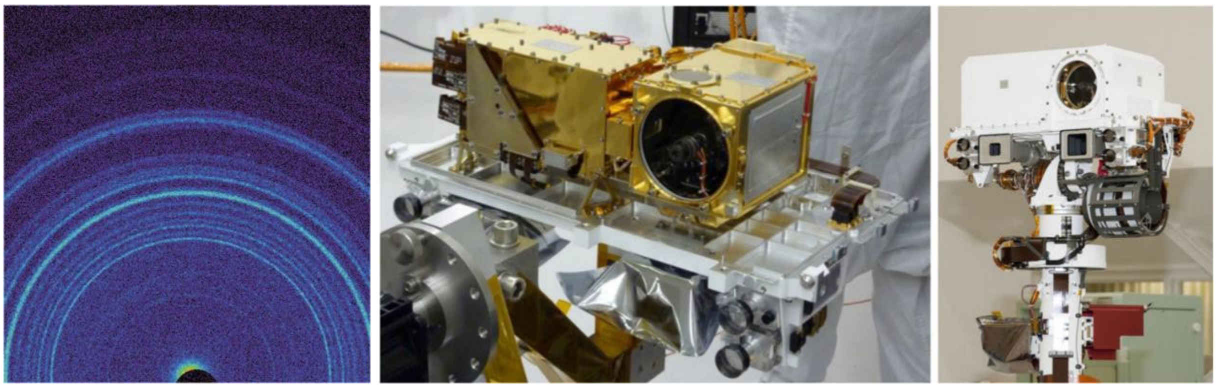
(a) (b)

FIG 10 – MSL parachute testing at the National Full-Scale Aerodynamics Complex wind tunnel (Cruz, 2013). EBMD departure from OVERFLOW unsteady CFD solution (Schoenenberger, 2009).

Mineralogy analysis

Multiphysics simulation offers a valuable avenue for enhancing mineralogy analysis in extreme environments. Simulating diverse conditions provides insights into mineral distribution and formation processes. For example, the Curiosity Rover's mineralogy analysis, utilising X-ray diffraction (XRD) and X-ray fluorescence (XRF) techniques, enabled the identification and quantification of Martian soil minerals (Figure 11a) (Bish, 2013). Instruments like ChemCam also directly detected minerals on the Martian surface, shedding light on weathering processes and mineral distribution (Figure 11b and 11c) (Fairén *et al*, 2015). These insights are crucial for future exploration and resource utilisation endeavours.

Despite the challenges the Martian environment poses, mineralogy analysis tools like CheMin and ChemCam have demonstrated resilience in extreme conditions, providing invaluable data for identifying potential resource sites on Mars. However, limitations in instrument sensitivity and the complexity of Martian soil composition underscore the need for advanced instrumentation for comprehensive mineralogical analysis (Fairén *et al*, 2015). Nevertheless, the success of mineralogy analysis on Mars showcases the adaptability of space exploration technologies, paving the way for future missions to explore even more demanding environments, such as deep-sea mining sites.



(a) (b) (c)

FIG 11 – (a) CheMin 2D XRD pattern of scoop 5, representing 26.9 hrs of integration time (Bish, 2013). ChemCam integration: (b) on the camera plate, (c) in the box (Maurice, 2012).

MARS SCIENCE LABORATORY (MSL) CURIOSITY ROVER STUDY CASE

MSL landed on Mars in August 2012 after almost a decade of preparation. It began formulation in 2003 and entered the implementation (build) phase in 2006 and Ramp Drive Test at NASA's Jet

Propulsion Laboratory (JPL), Pasadena, California, on September 10, 2010 (McGregor *et al*, 2010).

Designed to last two years, the MSL Curiosity rover surprises with a life span of more than four times longer. However, after one year of exploring Gale Crater, NASA JPL engineers noticed some wear on Curiosity's wheels in the form of dents and small 0.75 mm thick holes in the aluminium skin (Ackerman, 2021).

Holes and tears in the wheels worsened significantly during 2013 as Curiosity was crossing terrain studded with sharp rocks on the route from near its 2012 landing site to the base of Mount Sharp. Team members have used MAHLI systematically since then to watch for when any of the zigzag-shaped grousers begin to break. Figure 12 was taken on 19 March 2017, as part of a set used by rover team members to inspect the condition of the Rover's six wheels during the 1641st Martian day, or sol, of Curiosity's work on Mars (NASA JPL, 2017).

(a) (b)

FIG 12 – MSL left wheel wearing: (a) MAHLI full-wheel imagery of Curiosity's left-middle wheel taken on April 18, 2016 (sol 1315), (b) Detailed view of the inner surface of Curiosity's left front wheel on sol 411. Arrow points to tears (NASA JPL, 2017).

MLS' wheel damage appeared much faster than expected and kept increasing faster than JPL had anticipated. Even by 2014, the controllers made in the Rover's routing to slow down the appearance of dings and holes. *'They [the wheels] are taking damage. That is the surprise we got back at the end of last year'*, *'We always expected we would get some holes in the wheels as we drove. It's just the magnitude of what we're seeing that was the surprise.'* – Jim Erickson, Curiosity project manager at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, July 2014 (Howell and Dobrijevic, 2022).

This research takes inspiration from this event to learn the root cause of this failure and how to avoid this type of event through a comprehensive and iterative multiphysics simulation and design validation.

While physical model-based testing offers adaptability and tangible human insight, it has limitations regarding scalability and efficiency compared to virtual testing. Combining manual and virtual testing based on project requirements is often the most effective testing strategy.

A rover virtual twin simulation system can be helpful in many ways, such as obtaining an objective, cost-effective design, optimise design, testing and construction time, and improving component robustness as conditions can be varied, several inputs/outcomes investigated and critical situations can be analysed without technical or financial risks.

To fullfill those benefits, this research proposes a 'Multiphysics Modelling and Virtual Motion Simulation (MMVMS) approach aiming to design and test rover motion on real Martian conditions, including the hardness of the irregular terrain of the red planet, to investigate the forces affecting wheels performance, reduce their wearing and validate the wheel-damping capability. In this sense, the research first developed a detailed topology of a digital twin of MSL Curiosity rover systems and then designed all of them on a real scale. Afterwards, the system's performance was evaluated, and the mobility of the components was evaluated in a static set-up. Finally, the dynamics and performance of the MLS Curiosity rover's digital twin under real Martian terrain and environmental conditions were evaluated using its virtual twin.

MSL Curiosity Rover digital twin

Rover components – generative design

To create and define the Rover mechanism (Mechanism is a product whose components can be moved relative to each other according to certain predefined constraints.) from rover assembly and perform Kinematic simulation of various components like Wheels, Cameras, antennas and different types of sensors of Curiosity Rover. Mechanical System Design.

Assembly of Rover components

The holistic design and further simulation require an end-to-end mapping of all systems and components to provide fidelity to rover dynamics and behaviour. Engineering Connections were created to map all components and their interaction. These constraints or joints define a mechanical relation among all the Rover's components assembled through the MSL mechanisms, as seen in Figure 13.

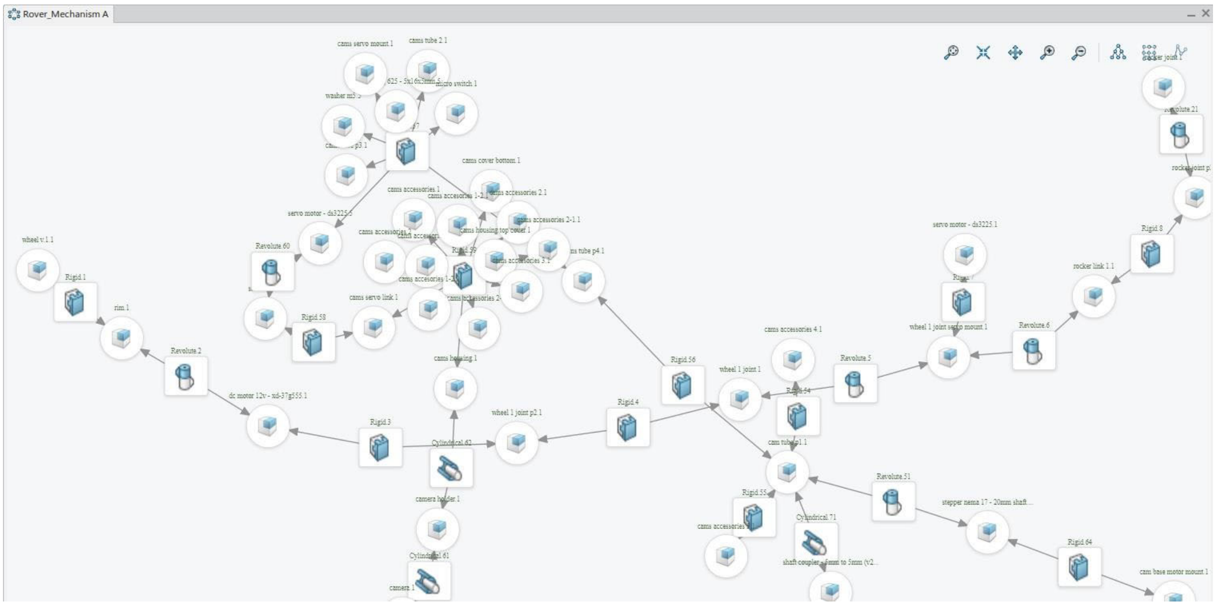


FIG 13 – MSL Curiosity Rover Mechanism topology sample (NB: whole Rover assembly topology cannot fit in a single image due to size constraints. Further information can be accessed via the corresponding author).

During the initial placement of the digital twin of MLS Curiosity rover's components, ensuring they do not cross or clash is fundamental. Using the advanced features of Generative Desing, an automatic interference check was performed between different sets of components of MSL's digital twin (Figure 14a). After analysing the above interference result, the initial position of the Rover components was corrected by changing the constraints and ensuring no components should clash during their respective movements (Figure 14b and 14c). This simulation and integrated testing of elements using real motion provided the best set of configurations of rover components by using available space to mount. Figure 14d depicts the placement of rover components after design testing and validation.

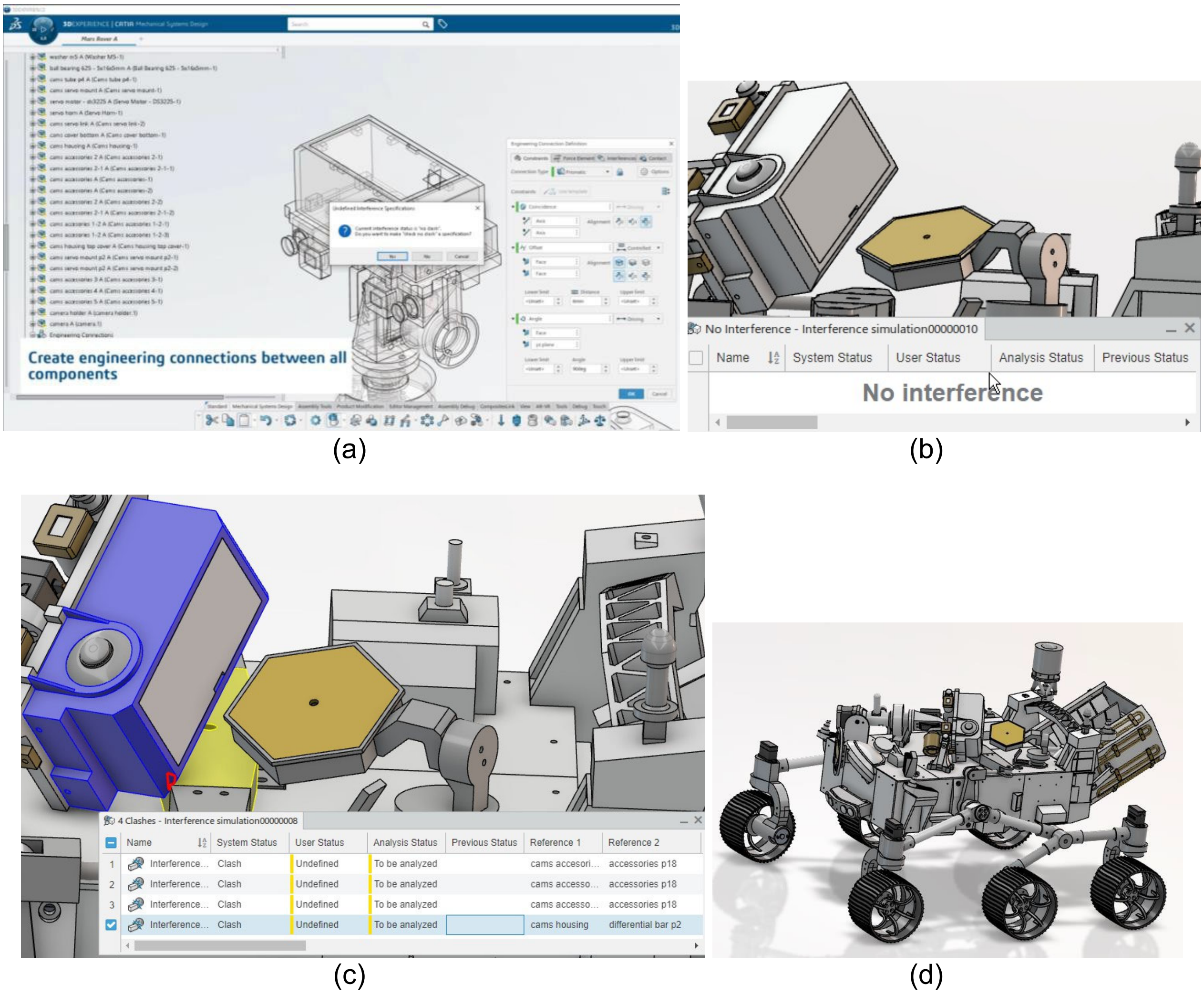


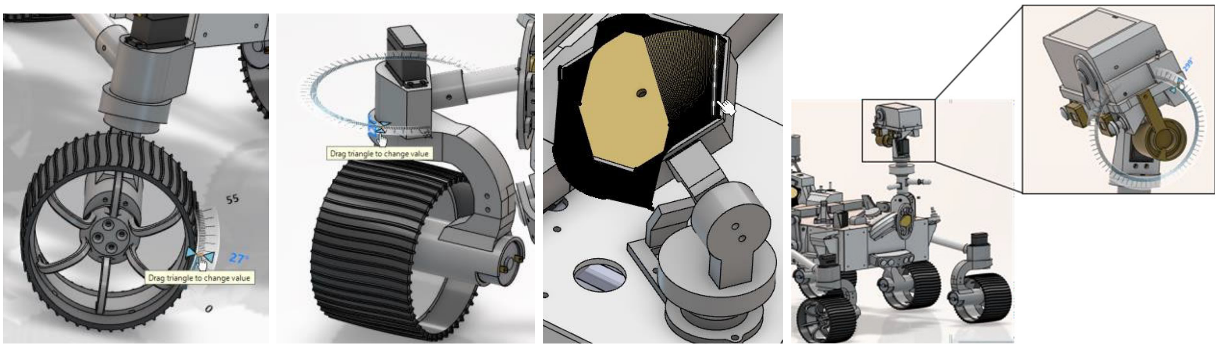
FIG 14 – MSL digital twin generative design: (a) Automatic Interference check, (b) Interference check in Rover assembly at the initial stage, (c) Assembly after removal of clash, (d) Component placements at the initial stage.

Mobility verifications of Rover components

Once the mechanisms were physically and correctly in place, all Rover's mechanisms were simulated together and simultaneously to visualise the movements of different components, giving a certain degree of freedom to each one of them and verifying flexibility and the maximum range of failure.

The research assessed that all components and systems were designed correctly and operating as per MSL scope. However, due to the large list of systems and the main inspiration of this research, the following chapter focuses on assessing the design, mobility performance and wearing of the main component of the motion systems, encompassing mobility (wheels and steering), communication (antennas) and sensory (camera). For the mobility system, the rotational movement of the wheel and steering movement system of the Curiosity rover's digital twin was simulated for each individual steering motor in the two front and two rear wheels. Thus, the four-wheel steering allows the Rover to swerve and curve, making arcing turns that allow it to turn in place at 360 degrees to avoid, navigate or traverse potential obstacles (Figure 15).

To ensure reliable and enduring communication, antennas should be designed following the desired path during Kinematic simulations to send radio waves at a low rate to the Deep Space Network (DSN) antennas on Earth. However, one of the main challenges to maintaining communications is keeping the direction of radiofrequency transmission at all times. Thus, the digital twin of MSL was designed using the same steerable antenna so that the Rover does not need to change positions to communicate with Earth. In addition to direction, antenna stability is also required to maintain latency. In this way, the DSN's radiofrequency, bandwidth and latency features were simulated on board of the MSL digital twin to verify the mechanical (Figure 15a and 15b) and telecommunication acceptability of the design under kinetic and kinematic conditions (Figure 15c). Finally, Panoramic Camera movement was simulated and assessed to capture three-dimensional 360 panorama pictures of the Martian surface. This stage aims to capture any physical interference in the path of cameras at any speed and traversing speed and ensure stability. Figure 15d shows the different movements of panoramic cameras.



(a) (b) (c) (d)

FIG 15 – Mobility verifications: (a) Rotational movement of wheel, (b) Steering movement of wheel, (c) Path traced by Rover antennas during kinematic simulation, (d) Camera movement and clearance simulation.

Dynamic multiphysics simulation in Martian conditions

The intricate mechanics of Rover motion dynamics were assessed using Simpack MBS®, a software for simulating and analysing multi-body systems, which is particularly useful in mechanical engineering for virtual prototyping and testing. Our approach seamlessly harmonised the precise data set of the Mars rover with the discrete terrain data set, setting a new standard for hybrid modelling excellence.

Central to our methodology was the meticulous preparation and conversion of terrain data, a critical step in ensuring the accuracy of our simulations. Anticipating potential computational bottlenecks, we optimised the CATIA tessellations and then exported terrain data as '.OBJ' files to Simpack MBS®. Additionally, we added a manual conversion process, where '.OBJ' data was transformed into '.RDF' (road definition file) format, filtering nodes and elements information to describe the RDF road surface through polylines and triangles. This resulting RDF file was flawlessly integrated into Simpack MBS®, facilitating Multi-Body Simulation (Srividhya, Sharma and Kumar, 2013).

While building our multi-body simulation model, every aspect was painstakingly tailored to emulate the gravitational conditions of Mars, with a gravity of -3.721 m/s^2 factored into our calculations. Parameters such as mass, the centre of gravity, and inertia were assigned to chassis, wheels, and suspension links, ensuring a real-life representation of the Rover's dynamics (Anon., n.d.)). We then defined the joints between bodies and added wheels mathematical models and finely tuned suspension characteristics.

We subjected the digital twin of MSL to ground testing on a flat track with varying slopes to conduct preliminary tests, analysing suspension behaviour and rover stability. With the benefit of Simpack features, we could easily switch the road within the simulation by changing it in the Road element properties.

Witnessing the Rover navigate and ascend a steep slope on Mars provided invaluable insights into wheel forces, suspension behaviour, body dynamics, and overall vehicle stability.

We evaluated the wheel forces essential for wheel damage calculations and assessed forces at different suspension link attachment points (Nuñez-Quispe, 2021). For this simulation, we observed peak loads of 3000 N per wheel. These forces can be used for structural simulation to determine the stresses in the components and for wheel wear. For this project, it was beyond the scope.

An additional body dynamics simulation, encompassing roll angle and wheel longitudinal slip, was conducted to ascertain the vehicle's stability under extreme driving conditions due to uneven surfaces (Yoshida, 2001). These simulations facilitate the replication of scenarios across a spectrum of virtual testing applications, from rigorous distress tracks on Mars to demanding mining environments, highlighting their versatility and relevance.

A dedicated test was conducted on the performance of front wheels to assess their behaviour and the vertical force components that affect the structure. The test was conducted by simulating a 15-degree inclination climbing path (Figure 16a), similar to the challenge faced in August 2023. Starting from motionless, the vertical force affecting each wheel was measured and recorded for the first 14 seconds. A significant stress was detected in the right wheel, which is likely due to the terrain and the climbing setting where the right wheel was the more exposed to and performed the more effort to climb. It is visible in the red line in Figure 16b that after the stress in the front right wheel to get traction, the left front wheel follows the same pattern with a 2-second delay, yet with slightly less intensity. This opens the hypothesis that the failure of the wheel of the real Rover can be primarily attributed to the stress suffered due to the imbalance of stress of the wheel during its journey. It also highlights the benefits of a digital twin not only for design and performance but also for mission planning as wearing and other possible failures can be predicted, and design, materials, plans, and routes can be adjusted to avoid or minimise damage and risks (Figure 16c and 16d). It echoes the conclusion of NASA JPL in its report about the incident: *The anomalous wheel wear suggests that loads and terrains representative of actual operational conditions were not adequately simulated during life testing* (NASA JPL, 2017).

The kinematic feature of the steering system of MSL Curiosity rover's digital twin was assessed under simulated real terrain conditions. The two front and two rear wheels have individual steering motors, allowing the simulation of stress and vertical forces during Turning–in–place movement. Throughout several simulations, including hard and soft obstacles, it was found that the driving loads in the turning-axis wheel exceed the normal range during regular trips (in movement). This rugged and sharp surface was tested to determine whether or not it could cause a metal puncture. While it was visually observed in the simulation, stress and vertical forces values obtained were inconclusive, yet a possible wearing element of wheels was not omitted.

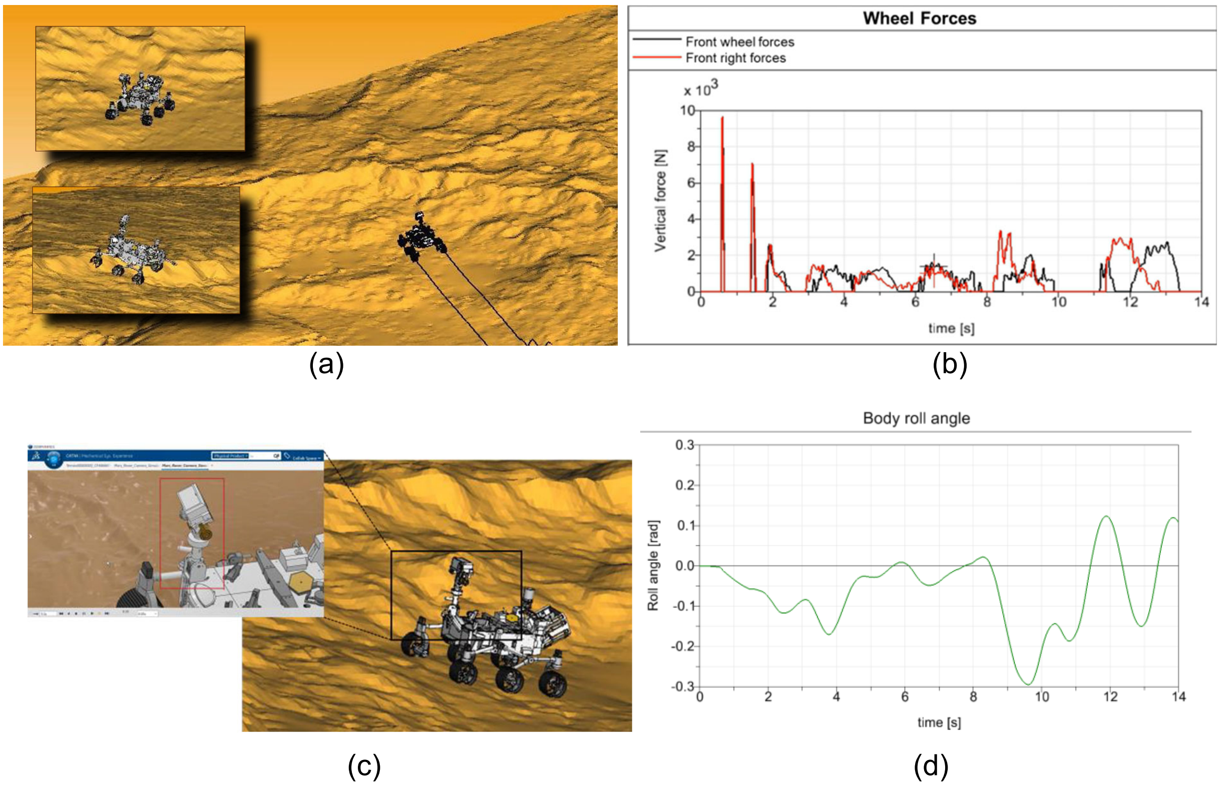


FIG 16 – (a) Dynamics on Mars terrain, (b) Multiphysics assessment: wheel's vertical forces, (c) Dynamic simulation camera assembly behaviour, (d) Multiphysics assessment: body roll angle.

Finally, in addition, the kinematic performance of the virtual twin was assessed using Computational Fluid Dynamics (CFD) analysis, simulating various environmental parameters—such as wind (Figure 17a), solar, and thermal conditions—that mirror those found on Mars. While solar and thermal conditions were found to have minimal effect on the structure and performance of the Rover, wind forces are an attention point. These forces do not have a significant impact on the speed and overall movement of the virtual twin. Nevertheless, the gap between structures such as cameras, body and suspension might generate a wind acceleration effect (Figure 17b). It can eventually damage critical components highly exposed to those forces, such as those mentioned above. The simulation did not identify any component fatigue due to wind forces. However, the timespan was relatively smaller (days) compared to the 12 years that the actual Rover has been traversing across the red planet and exposed to environmental forces. An extended simulation, incorporating cumulative effects of forces and wearing, could provide important insights into the Rover's behaviour under Martian-like conditions, facilitating informed decision-making in mission planning and execution.

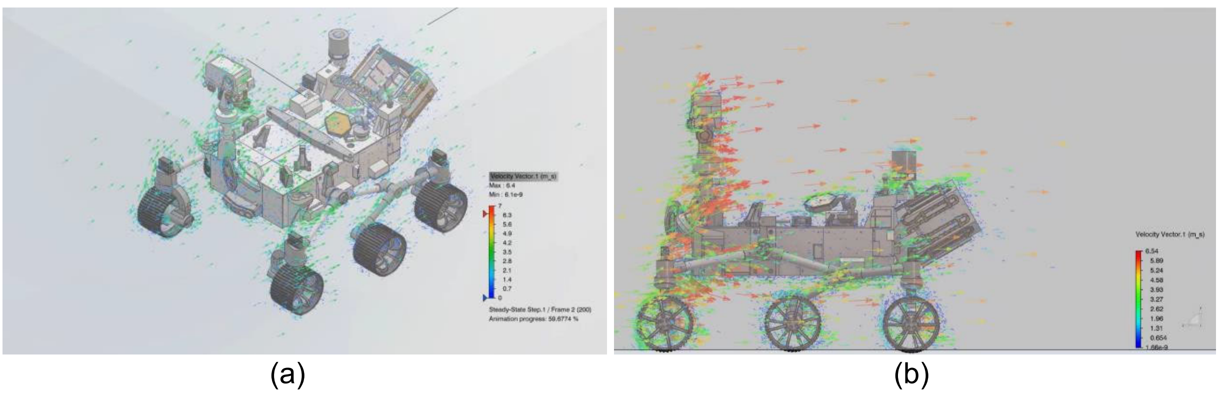


FIG 17 – Fluid dynamic simulation: (a) Wind speed simulation in static conditions; (b) Wind speed simulation vectors in motion.

CONCLUSIONS

The exploration and exploitation of mineral resources in extreme environments on Earth or in space missions pose multidimensional challenges, including data scarcity, uncertainty, and the imperative for robust equipment. Comprehensive, innovative solutions such as digital twins, generative design, and multiphysics simulation systems offer promising avenues for mitigating risks and ensuring mission success. Digital twins facilitate informed decision-making throughout an asset's life cycle by providing virtual representations of physical assets. At the same time, generative design streamlines the design process by swiftly translating requirements into viable shapes. Integrating advanced CAD design tools and multiphysics simulation enables early and accurate assessments under actual environmental conditions, accelerating the design process and ensuring equipment reliability. Hierarchical simulation emerges as a valuable approach for managing the intricacies of simulation models, facilitating effective evaluation of performance criteria.

Moreover, the Mars Science Laboratory (MSL) Curiosity rover study case underscores the importance of thorough simulation and design validation in mitigating unexpected challenges. The unexpected wear on Curiosity's wheels, carefully simulated by NASA JPL prior to design, highlights the need for comprehensive simulation under uncertainties to understand failure mechanisms and prevent similar occurrences. Inspired by this event, a multiphysics modelling and virtual motion simulation (MMVMS) approach is proposed to design and test rover motion under real Martian conditions, optimising component robustness and performance. The digital twin of the MSL Curiosity rover, encompassing generative design and mobility verifications, offers insights into component behaviour and system dynamics. Simulation using Simpack MBS® and computational fluid dynamics (CFD) analysis provides a detailed understanding of rover dynamics and performance under various environmental conditions. The integration of terrain data and precise modelling of gravitational effects ensures the accuracy of simulations, while dedicated tests assess wheel forces, suspension behaviour, and structural integrity. Furthermore, kinematic simulations of the steering system and CFD analysis of environmental parameters demonstrate the versatility and applicability of the MMVMS approach in mission planning and execution. While challenges such as wind forces and component fatigue persist, extended simulations hold promise for providing crucial insights into long- term rover behaviour and informing future mission strategies. In essence, the synergistic integration of advanced technologies and comprehensive simulation methodologies offers a robust framework for addressing the challenges of space exploration and resource exploitation in extreme environments, paving the way for sustainable and successful missions beyond Earth's boundaries.

REFERENCES

Ackerman, E, 2021. If Necessary, Mars Rover Curiosity Could Rip Its Own Wheels Off to Stay Mobile [online], *IEEE Spectrum*. Available from: <https://spectrum.ieee.org/if-necessary-mars-rover-curiosity-could-rip-its-own-wheels-off-to-stay-mobile>

Agarwal, S, 2021. Surprising simplicity in the modeling of dynamic granular intrusion, *Applied Sciences And Engineering*, 7(17):10.

Fairén, A G, Losa-Adams, E, Gil-Lozano, C, Gago-Duport, L, Uceda, E R, Squyres, S W, Rodríguez, J A P, Davila, A F and McKay, C P, 2015. Tracking the weathering of basalts on Mars using lithium isotope fractionation models, *Geochem Geophys Geosyst*, 16:1172–1197.

Bhandari, P and Anderson, K R, 2013. CFD Analysis For Assessing The Effect Of Wind On The Thermal Control Of The Mars Science Laboratory Curiosity Rover, in *43rd International Conference on Environmental Systems,* p 3325.

Bish, D L, 2013. X-ray Diffraction Results from Mars Science Laboratory: Mineralogy of Rocknest at Gale Crater, *Science*, vol 6.

Botín-Sanabria, D M, Mihaita, A-S, Peimbert-García, R E, Ramírez-Moreno, M A, Ramírez-Mendoza, R A, de Lozoya-Santos, J, 2022. Digital twin technology challenges and applications: A comprehensive review, *Remote Sens (Basel),* 14:1335.

Bryan, K and Dempsey, H, 2023. 'Playing with fire': the countdown to mining the deep seas for critical minerals, *Financial Times*.

Cameron, J, Jain, A, Huntsberger, T, Sohl, G and Mukherjee, R, 2009. Vehicle-Terrain Interaction Modeling and validation for Planetary Rovers, Jet Propulsion Laboratory (JPL), NASA.

Choudhary, R, Papalambros, P Y and Malkawi, A M, 2005. Simulation-based design by hierarchical optimization, Proceedings of the Ninth International IBPSA Conference, Citeseer.

Cruz, J R, 2013. Parachute Models Used in the Mars Science Laboratory, Daytona Beach, AIAA, 27.

Do, S, Ho, K, Schreiner, S S, Owens, A C and de Weck, O L, 2014. An independent assessment of the technical feasibility of the mars one mission plan, International Astronautical Federation.

Dräger, 2024. Deep, deeper, deepest [online], Jet Propulsion Laboratory (JPL), NASA. Available from: <https://www.draeger.com/Content/Documents/Content/the-ten-deepest-mines-of-the-world.pdf> [Accessed: 23 March 2024].

Erkoyuncu, J A, Butala, P and Roy, R, 2018. Digital twins: Understanding the added value of integrated models for through-life engineering services, *Procedia Manuf*, 16:139–146.

Forget, F, Wordsworth, R, Millour, E, Madeleine, J-B, Kerber, L, Leconte, J, Marcq, E and Haberle, R M, 2013. 3D modelling of the early Martian climate under a denser CO_2 atmosphere: Temperatures and CO_2 ice clouds, *Icarus,* 222:81–99.

Fraser, S D, 2009. Power system options for mars surface exploration: Past, present and future, *Mars: Prospective Energy and Material Resources*, 1–23.

Gao, J, Liu, M, Li, P, Laghari, A A, Javed, A R, Victor, N and Gadekallu, T R, 2023. Deep Incomplete Multi-View Clustering Via Information Bottleneck for Pattern Mining of Data in Extreme-Environment IoT, *J IEEE Internet Things*.

Glaessgen, E and Stargel, D, 2012. The digital twin paradigm for future NASA and US Air Force vehicles, in *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference; 20th AIAA/ASME/AHS Adaptive Structures Conference*, 1818.

Griffin, A, 2020. Final Call for NASA's RASSOR Bucket Drum Challenge, *NASA*. Available from: <https://blogs.nasa.gov/kennedy/tag/rassor/> [Accessed: 24 April 2024].

Helbig, C, Bauer, H-S, Rink, K, Wulfmeyer, V, Frank, M and Kolditz, O, 2014. Concept and workflow for 3D visualization of atmospheric data in a virtual reality environment for analytical approaches, *Environ Earth Sci*, 72:3767–3780.

Ho, K, de Weck, O L, Hoffman, J A and Shishko, R, 2014. Dynamic modelling and optimization for space logistics using time-expanded networks, in 65th International Astronautical Congress, Toronto.

Howell, E and Dobrijevic, D, 2022. Curiosity rover: The ultimate guide [online], *Space.com*. Available from: <https://www.space.com/17963-mars-curiosity.html>

Kaufman, M, 2013. Mars Rover Curiosity Has First Big Malfunction [online], *Natl Geogr Mag*, Available from: <https://www.nationalgeographic.com/science/article/130301-mars-rover-curiosity-malfunction-science-space-nasa-jpl> [Accessed: 24 April 2024].

Khan, S and Awan, M J, 2018. A generative design technique for exploring shape variations, *Advanced Engineering Informatics*, 38:712–724.

Kornfeld, R P, 2014. Verification and Validation of the Mars Science Laboratory/Curiosity Rover Entry, Descent and Landing System, *JSR Spacecraft Rockets*, 51(4):1251–1269.

Krish, S, 2011. A practical generative design method, *Computer-Aided Design*, 43:88–100.

Li, W, 2013. ROSTDyn: Rover simulation based on terramechanics and dynamics, *Journal of Terramechanics*, 50:199–210.

Luna, J J, 1993. Hierarchical relation in simulation models, in *Proceedings of the 25th Conference on Winter Simulation*, pp 132–137.

Maurice, S, Wiens, R C, Saccoccio, M, Barraclough, B, Gasnault, O, Forni, O, Mangold, N, Baratoux, D, Bender, S, Berger, G and Bernardin, J, 2012. The ChemCam Instrument Suite on the Mars Science Laboratory (MSL) Rover: Science Objectives and Mast Unit Description, *Space Science Reviews*, 170:95–166.

McGregor, V, Jackson, R, Greicius, T and Hartono, N, 2010. Ramp Drive Test for Curiosity Mars Rover [online], *NASA*. Available from: <https://www.jpl.nasa.gov/images/pia13383-ramp-drive-test-for-curiosity-mars-rover>

Miley, G H, Yang, X and Rice, E, 2009. Distributed power sources for mars, *Mars: Prospective Energy and Material Resources*, pp 213–239 (Springer).

NASA Jet Propulsion Laboratory (JPL), 2017. Premature Wear of the MSL Wheels [online], Jet Propulsion Laboratory (JPL), NASA. Available from: <https://llis.nasa.gov/lesson/22401/> [Accessed: 12 April 2024].

NASA, 2019. Mars Exploration Rovers: Spirit and Opportunity [online], NASA. Available from: <https://science.nasa.gov/mission/mars-exploration-rovers-spirit-and-opportunity/> [Accessed: 08 April 2024].

Nuñez-Quispe, J J, 2021. Design and Simulation of a Rover CanSat Non-pneumatic Wheel: Preliminary Study for a Certain Test Obstacle Path, in *Proceedings of the 12th International Conference on Mechanical and Aerospace Engineering (ICMAE)*, pp 484–488.

Paar, P, 2006. Landscape visualizations: Applications and requirements of 3D visualization software for environmental planning, *Comput Environ Urban Syst*, 30:815–839.

Palaia IV, J E, Homnick, M S, Crossman, F, Stimpson, A and Truett, J, 2009. Economics of energy on Mars, in *Mars: Prospective Energy and Material Resources*, pp 369–400 (Springer).

Paris, A, 2008. Thermal Design of the Mars Science Laboratory Powered Descent Vehicle, SAE Technical Paper 2008-01–2001, 18 p.

Pelech, T M, Sibille, L, Dempster, A and Saydam, S, 2021. A framework for Off-Earth mining method selection, *Acta Astronaut*, 181:552–568.

Planetary Society, The, 2024. Cost of MSL Curiosity [online], *The Planetary Society*. URL <https://www.planetary.org/space-policy/cost-of-msl-curiosity> [Accessed: 24 April 2024].

Popa-Simil, L, 2009. The Evolution of Nuclear Power Generation for Mars, in *Mars: Prospective Energy and Material Resources*, pp 175–211 (Springer).

Quattrocchi, G, Pittari, A, Dalla Vedova, M D and Maggiore, P, 2022. The thermal control system of NASA's Curiosity, rover: a case study, in *IOP Conference Series: Materials Science and Engineering*, 1226(1):012113.

Rapp, D and Rapp, D, 2016. In situ utilization of indigenous resources, *Human Missions to Mars: Enabling Technologies for Exploring the Red Planet*, pp 273–382.

Saydam, S, Tapia-Cortez, C, de Roche, T and Dempster, A, 2015. An evaluation of mars water extraction mission, in *26th Annual General Meeting and Conference, Society of Mining Professors (SOMP),* pp 21–26.

Schoenenberger, M, 2009. Aerodynamic Challenges for the Mars Science Laboratory Entry, Descent and Landing, *AIAA*, p 29.

Senatore, C, 2014. Modeling and Validation of Mobility Characteristics of the Mars Science Laboratory Curiosity Rover, *Engineering, Environmental Science, Physics,* 8.

Sengupta, A, Steltzner, A, Comeaux, K, Candler, G, Barnhardt, M, Pantano, C, Bell, J, Heineck, J T and Schairer, E, 2008. Results from the Mars Science Laboratory Parachute Decelerator System Supersonic Qualification Program, in *2008 IEEE Aerospace Conference*, pp 1–15.

Shafto, M, Conroy, M, Doyle, R, Glaessgen, E, Kemp, C, LeMoigne, J and Wang, L, 2010. Draft modeling, simulation, information technology and processing roadmap, *Technology area*, 11:1–32.

Shea, K, Aish, R and Gourtovaia, M, 2005. Towards integrated performance-driven generative design tools, *Autom Constr,* 14:253–264.

Srividhya, G, Sharma, G and Kumar, H N S, 2013. Software for modelling and analysis of rover on terrain, in *Proceedings of Conference on Advances In Robotics*, pp 1–8.

Talkhestani, B A, Jazdi, N, Schloegl, W and Weyrich, M, 2018. Consistency check to synchronize the Digital Twin of manufacturing automation based on anchor points, *Procedia CIRP*, 72:159–164.

Tapia Cortez, C, Saydam, S, Coulton, J and Sammut, C, 2018. Alternative techniques for forecasting mineral commodity prices, *Int J Min Sci Technol*, 28:309–322. https://doi.org/10.1016/j.ijmst.2017.09.001

Tapia, C and Hay, B, 2023. Above and Beyond NPV: Determining the Life of Mine from an Economic Perspective, in *Proceedings of the Life of Mine Conference 2023*, pp 147–152 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Thangavelautham, J, Chandra, A and Jensen, E, 2019. Autonomous Multirobot Technologies for Mars Mining Base Construction and Operation, *International Astronautical Congress 2019*, 15 p. https://doi.org/10.48550/arXiv.1910.03829

Van Der Horn, E and Mahadevan, S, 2021. Digital Twin: Generalization, characterization and implementation, *Decis Support Syst,* 145:113524.

Voit, E O, Balthis, W L and Holser, R A, 1995. Hierarchical Monte Carlo modeling with S-distributions: concepts and illustrative analysis of mercury contamination in king mackerel, *Environ Int*, 21:627–635.

Yoshida, K, 2001. Motion dynamics simulations and experiments of an exploration rover on natural terrain, in *Proceeding of the 6th International Symposium on Artificial Intelligence and Robotics and Automation in Space*, pp 7–8.

Zacny, K and Bar-Cohen, Y, 2009. Drilling and excavation for construction and in-situ resource utilization, in *Mars: Prospective Energy and Material Resources,* pp 431–459 (Springer).

Zhou, F, Arvidson, R E, Bennett, K, Trease, B, Lindemann, R, Bellutta, P, Iagnemma, K and Senatore, C, 2014. Simulations of mars rover traverses, *J Field Robot*, 31:141–160.

Deep-sea mining considerations and environment impact – an overview

M Torok[1], S Akdag[2], S Saydam[3], I Canbulat[4], J Katupitiya[5] and W Midgley[6]

1. Research Assistant, UNSW Sydney, Kensington NSW 2052.
   Email: mitchell.torok@student.unsw.edu.au
2. Postdoctoral Fellow, UNSW Sydney, Kensington NSW 2052. Email: s.akdag@unsw.edu.au
3. Professor, UNSW Sydney, Kensington NSW 2052. Email: s.saydam@unsw.edu.au
4. Professor, UNSW Sydney, Kensington NSW 2052. Email: i.canbulat@unsw.edu.au
5. Associate Professor, UNSW Sydney, Kensington NSW 2052. Email: j.katupitiya@unsw.edu.au
6. Senior Lecturer, UNSW Sydney, Kensington NSW 2052. Email: w.midgley@unsw.edu.au

INTRODUCTION

The green energy transition is expected to require a range of valuable minerals, which could be supplied through deep-sea polymetallic nodule mining. Deep-sea polymetallic nodules are mineral deposits with a composition well suited to produce lithium batteries, which are expected to be a necessary energy storage solution (Diouf and Pode, 2015; Paulikas *et al*, 2020) for the energy transition. By 2050 the annual demand for both cobalt and lithium is estimated to increase by around 450 per cent from 2018 levels (Hund *et al*, 2023), with the annual demand for nickel being greater than 2 million tons, and copper greater than 1 million tons. Polymetallic nodule mining is well positioned to provide these minerals in the near future.

An intricate and comparatively unexplored ecosystem thrives within and surrounding the nodule fields (Smith *et al*, 2008). Deep-sea mining operations have the potential to disrupt and permanently damage this ecosystem through introduced pollution, artificial noise and light, and habitat destruction. Hence, there is a pressing need for new engineering and scientific endeavours to focus on developing new technologies to reduce any environmental impact from mining.

DEEP-SEA POLYMETALLIC NODULE MINING

Deep-sea polymetallic nodules are mineral deposits consisting primarily of manganese and iron oxides (Figure 1). Nodules form through precipitation over millions of years, during which rare-earth minerals are included in the precipitation such as nickel, copper, cobalt, molybdenum, and lithium (Hein *et al*, 2013). Polymetallic nodules are situated within and on top of abyssal plains at depths of 4000 m to 6000 m, often lying exposed on the seabed. They have a black appearance and range in size, typically having a diameter of approximately 150 mm (Sharma, 2018). Estimates are rough due to the nature of the environment; however, it is suggested that nodule fields could have an average density of 5–10 kg of nodules per square metre (Sharma, 2018; Mucha and Wasilewska-Błaszczyk, 2020). A 75 000 km^2 mining site in the Clarion-Clipperton Zone (CCZ) is estimated to hold 375 million tons of wet nodules which would provide approximately 2 million tons of nickel and copper, and 200 000 tons of cobalt (Sharma, 2018; Borkowski *et al*, 2022). It has been suggested that there could be 34 billion tons of nodules in the CCZ (Morgan, 2000).

FIG 1 – Deep-sea Polymetallic nodules (left: appearance on seabed, middle: close up, right: cross) (Piper and Williamson, 1981).

Activities within deep-sea mining can be broken into four classifications: exploration, exploitation, monitoring, and closure. Exploration is focused on researching polymetallic nodule location and composition, and the surrounding ecosystems. Exploitation is the process of mining the nodules, while monitoring relates to the systems used to supervise the environmental impact of exploitation. Finally, closure is the process of rehabilitating a mined site. These classifications are used for defining phases and technology related to deep-sea mining.

Various exploitation systems have been proposed since the 1970s (Kang and Liu, 2021), however they all follow a similar design and approach (Figure 2) (Cheng *et al*, 2023). Designs commonly consist of slow-crawling machines, which use a mechanical or hydraulic system to lift and collect the top seabed layer (approximately 100 mm) which contains the nodules and sediment. The resulting slurry is then pumped to a surface vessel, where the nodules are separated. The by-product (sediment and biomass) is then pumped back down into the ocean through a discharge pipe creating a dewatering plume (Liu *et al*, 2023; Hong *et al*, 2010).

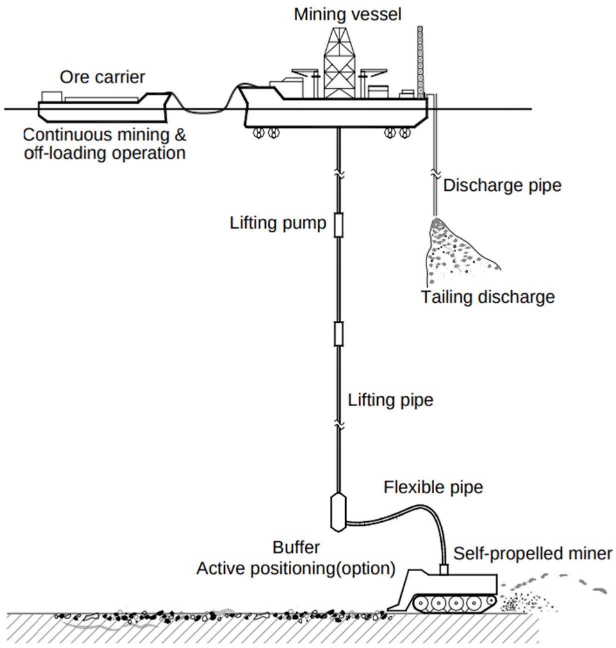


FIG 2 – Polymetallic nodule exploitation system overview (Hong *et al*, 2010).

The International Seabed Authority (ISA) is responsible for creating the deep-sea mining regulations as well as issuing contracts related to seabed activities (International Seabed Authority, 2024). To date no exploitation contracts have been awarded, however small-scale exploitation trails approved by the ISA have been conducted. Most recently, The Metals Company, and associated company Allseas performed a nodule collection trail in late 2022 (The Metals Company, 2023).

Unique plants and animals reside within the abyssal polymetallic nodule fields and may require the conditions provided by the nodules to survive (Vanreusel *et al*, 2016). Work has been conducted to document and estimate the extent of deep-sea biodiversity (Smith *et al*, 2008), with research suggesting that there are 1.48 individuals per metre squared within the CCZ (Morgan, 2000). Additionally, it has been noted that species' community structures vary substantially over spaces of 1000 km or less (Smith *et al*, 2008). Due to this it is estimated that each mine site may destroy a significant number of unique undiscovered species.

Currently proposed mining systems can generate significant sediment plumes from the collection and dewatering processes. Due to a long settling time and movement induced by ocean currents, these sediment plumes have the potential to travel long distances impacting unmined sites (Global Sea Mineral Resources NV, 2018). Suspended sediment and increased turbidity can restrict and limit the existing fauna's ability to survive (Simon-Lledó *et al*, 2019). It has been shown that even low concentrations of suspended sediment can have a serious negative effect on organisms, with long-term exposure increasing damage to the ecosystem (Levin *et al*, 2016).

RECOMMENDATIONS

Rather than resorting to conventional seabed mining methods, autonomous underwater precision robotics could be used to collect a specific subset of nodules. This approach has the potential to reduce sediment disturbances and allow for selective nodule collection avoiding those crucial to the local fauna, reducing the environmental impact. An individual agent may not match the efficiency of conventional mining vehicles; however, a multi-agent swarm system could overcome this limitation while offering benefits like enhanced localisation.

If existing deep-sea mining techniques are to be used for exploitation, more research should be undertaken to explore the created sediment plumes. Methods and techniques need to be developed for depositing the dewatering plume to minimise its impact on surrounding sites. It is also important to research and develop monitoring plans to assess the impact on and around the mining site over an extended period. After mining operations have finished there may be opportunities to assist in environment rehabilitation through artificial nodules. However more long-term research is required to verify and demonstrate the effectiveness of deep-sea rehabilitation techniques.

REFERENCES

Borkowski, P J, Abramowski, T, Szada-Borzyszkowska, M and Szada-Borzyszkowski, W, 2022. Comminution of Polymetallic Nodules with a High-Pressure Water Jet, *Materials*, 15(22):8228. https://doi.org/10.3390/ma15228228

Cheng, Y, Dai, Y, Zhang, Y, Yang, C and Liu, C, 2023. Status and Prospects of the Development of Deep-Sea Polymetallic Nodule-Collecting Technology, *Sustainability*, 15(5):4572. https://doi.org/10.3390/su15054572

Metals Company, The, 2023. Cyclone separator overflow, *The Metals Company,* Available from: <https://metals.co/cyclone-separator-overflow/> [Accessed):21 January 2024].

Diouf, B and Pode, R, 2015. Potential of lithium-ion batteries in renewable energy, *Renewable Energy*, 76:375–380. https://doi.org/10.1016/j.renene.2014.11.058

Global Sea Mineral Resources NV, 2018. Environmental Impact Statement, Ref Doc ISA_EIA_2018_GSRNOD2019, April 1st, 2018.Hein, J R, Mizell, K, Koschinsky, A and Conrad, T A, 2013. Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources, *Ore Geology Reviews*, 51:1–14. https://doi.org/10.1016/j.oregeorev.2012.12.001

Hong, S, Kimg, H-W, Choi, J-S, Yeu, T-K, Park, S-J, Lee, C-H and Yoon, S, 2010. A Self-Propelled Deep-Seabed Miner and Lessons From Shallow Water Tests, *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering (OMAE),* pp 75–86. https://doi.org/10.1115/OMAE2010-20313

Hund, K, Porta, D, Fabregas, T, Laing, T and Drexhage, J, 2023. *Minerals for Climate Action*: *The Mineral Intensity of the Clean Energy Transition.* https://doi.org/10.1596/40002

Kang, Y and Liu, S, 2021. The development history and latest progress of deep-sea polymetallic nodule mining technology, *Minerals*, 11(10):1132. https://doi.org/10.3390/min11101132

Levin, L A, Mengerink, K, Gjerde, K M, Rowden, A A, Van Dover, C L, Clark, M R, Ramirez-Llodra, E, Currie, B, Smith, C R, Sato, K N, Gallo, N, Sweetman, A K, Lily, H, Armstrong, C W and Brider, J, 2016. Defining ‘serious harm’ to the marine environment in the context of deep-seabed mining, *Marine Policy*, 74:245–259. https://doi.org/10.1016/j.marpol.2016.09.032

Liu, Z, Liu, K, Chen, X, Ma, Z, Lv, R, Wei, C and Ma, K, 2023. Deep-sea rock mechanics and mining technology: State of the art and perspectives, *International Journal of Mining Science and Technology*, 33(9):1083–1115. https://doi.org/10.1016/j.ijmst.2023.07.007

Morgan, C L, 2000. Resource estimates of the Clarion-Clipperton manganese nodule deposits, in *Handbook of Marine Mineral Deposits* (ed: Y Cronan), 1st edition, 26 p (Routledge: London). https://doi.org/10.4324/9780203752760

Mucha, J and Wasilewska-Błaszczyk, M, 2020. Estimation accuracy and classification of polymetallic nodule resources based on classical sampling supported by seafloor photography (Pacific ocean, clarion-clipperton fracture zone, iom area), *Minerals*, 10(3):263. https://doi.org/10.3390/min10030263

International Seabed Authority, 2024. Organs of the International Seabed Authority, *International Seabed Authority,* Available from: <https://www.isa.org.jm/organs/> [Accessed: 21 January 2024].

Paulikas, D, Katona, S, Ilves, E and Ali, S H, 2020. Life cycle climate change impacts of producing battery metals from land ores versus deep-sea polymetallic nodules, *Journal of Cleaner Production*, 275:123822. https://doi.org/10.1016/j.jclepro.2020.123822

Piper, D Z and Williamson, M E, 1981. Mineralogy and composition of concentric layers within a manganese nodule from the North Pacific Ocean, *Marine Geology*, 40(3–4):255–268. https://doi.org/10.1016/0025-3227(81)90143-2

Sharma, R (ed), 2018. *Deep-Sea Mining Resource Potential, Technical and Environmental Considerations* (Cham Springer International Publishing). Simon-Lledó, E, Bett, B J, Huvenne, V A I, Köser, K, Schoening, T, Greinert, J and Jones, D O B, 2019. Biological effects 26 years after simulated deep-sea mining, *Scientific Reports*, 9(1). https://doi.org/10.1038/s41598-019-44492-w

Smith, C R, Lambshead, J D, Rogers, A D and Gooday, A J, 2008. *Biodiversity, Species Ranges and Gene Flow in the Abyssal Pacific Nodule Province*: *Predicting and Managing the Impacts of Deep Seabed Mining*.

Vanreusel, A, Hilario, A, Ribeiro, P A, Menot, L and Arbizu, P M, 2016. Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna, *Scientific Reports*, 6:26808. https://doi.org/10.1038/srep26808

Effects of sulfate and chloride ions in acidic environments on the micro properties of granite

H Yu[1], C Zhang[2], H Chen[3], I Canbulat[4] and S Saydam[5]

1. PhD student, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: haida.yu@unsw.edu.au
2. Senior Lecturer, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: chengguo.zhang@unsw.edu.au
3. Postdoc, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: honghao.chen@unsw.edu.au
4. Professor, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: ismet.canbulat@unsw.edu.au
5. Professor, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: serkan.saydam@unsw.edu.au

ABSTRACT

Natural rocks are frequently exposed to groundwater and complex geological conditions. Environments with water presence are more susceptible to chemical corrosion, which notably affects rock's micro properties. Generally, the pH of acid mine drainage in hard rock mines can be low to 5, and the pH of quarrying waste deposits can be below 3. With the expanding scope of mining engineering in aquifers and salty areas, chemical corrosion can also caused by different types and concentrations of anions. The anions can significantly affect rock's mechanical properties. Therefore, it is critical to emphasise the impact of anion and acid on the mechanical and micro characteristics of rock. This paper commences with an introduction to representative corrosive environments. Then the UCS tests are conducted on granite samples corroded by chloride ions and sulfate ions. Anion has negative effects on the strength of granite. The reason is that certain minerals can react and be dissolved by anions and hydrogen ions, such as Al_2O_3. Furthermore, the scanning electron microscope (SEM) shows that the roughness of the fracture surface increases with the anion concentration. The effect of acid is notably more pronounced than anion on the micro properties of granite. The initiated fissures and pores also increase with the concentration of SO_4^{2-} and Cl^- ions, which is the micro explanation for the impact of anion on rock strength and stability. Subsequently, the permeability of the granite specimens is tested. The reason that granite performs insensitivity to acid and anion is attributed to its low permeability and high content of inactive oxides, such as quartz. To summarise, anionic and acidic conditions can slightly deteriorate the mechanical and micro properties of granite. While SO_4^{2-} demonstrates a higher level of corrosiveness on granite than Cl^-.

INTRODUCTION

Acidic groundwater is commonly encountered in the wider range of mining and geological engineering. Huo *et al* (2022) investigated the strain energy and microstructure of sandstone soaked in HCl and H_2SO_4 solutions with different pH. Geng *et al* (2023) analysed the pore characteristics and strength of sandstone after treatment with HCl and HF solutions. Sun *et al* (2023) studied the features of granite under water-rock interaction. Acid erosion has garnered considerable attention due to its threat to the stability of the rock.

Usually, acid drainage water in mines comprises various concentrations of sulfate ions (Fernando *et al,* 2018). Some metal mines in Queensland, Australia, are also rich in sulfate, nitrate, chloride, and phosphorus oxides. These anions also exhibit a significant corrosiveness on the microstructure of rock in acidic environments (Han *et al,* 2013; Qiao, Wang and Huang, 2016). Thus, it is important to reveal the coupled impact of acid and anion on rock's micro and mechanical properties.

EXPERIMENTAL SET-UP

The red granite used in this experiment was obtained from Sydney. The rock was cored into specimens with a diameter of 5.45 cm and a height of 10.90 cm, following the requirements of the ISRM. The granite specimens were dried in the oven until the weight didn't change by more than 0.1 g. Then, they were soaked in solutions at 28°C for ten days. The concentrations of the salt in acid solutions are listed in Table 1. After immersion, all samples were dried. Finally, the uniaxial tests on compression strength and permeability were conducted. And the microscope images were obtained.

TABLE 1

The concentration of NaCl in HCl solutions and Na_2SO_4 in H_2SO_4 solutions.

Number	Acid	pH	Solute	Anion concentration (mol/L)
1	-	7	Deionised water	-
2	HCl	2	NaCl	0.01
3	HCl	2	NaCl	3
4	H_2SO_4	2	Na_2SO_4	0.01
5	H_2SO_4	2	Na_2SO_4	3

RESULT AND ANALYSIS

Variation trend of the strength

The uniaxial compression strength of the granite specimens is shown in Figure 1. After immersion in HCl and H_2SO_4 solutions with a concentration of 0.01 mol/L, the strength of the specimens decreased by 7.48 per cent and 7.67 per cent. It indicates that sulfate ions have a more significant effect than chloride ions on the strength of granite. While in 3 mol/L Cl^- and SO_4^{2-} solutions, the strength decreased by 4.73 per cent and 5.38 per cent, compared to specimens soaked in 0.01 mol/L solutions. This suggests that acid has a stronger impact on the granite's strength than anions.

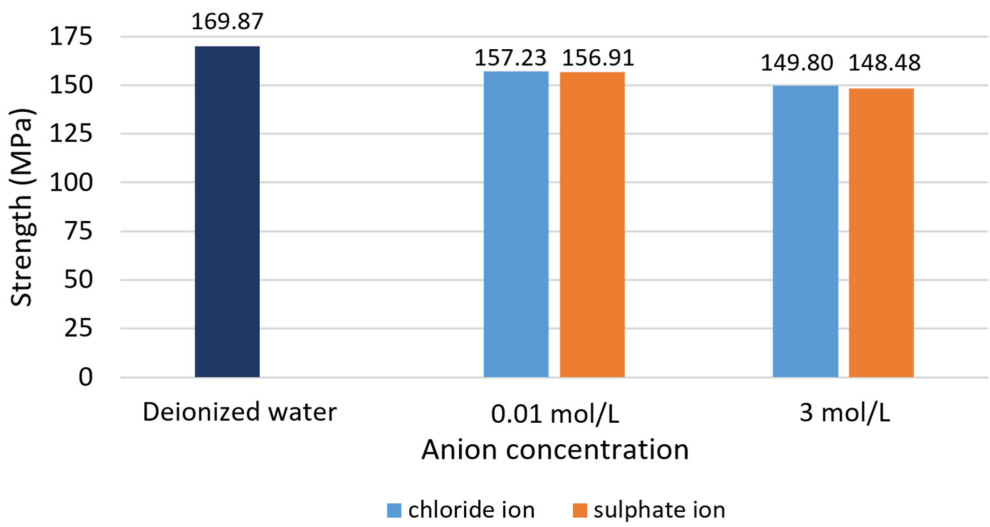


FIG 1 – Variation trend of granite strength with different concentrations of NaCl and Na_2SO_4 solutions.

Analysis of the micro properties

The scanning electron microscope image of the granite fragments is shown in Figure 2. In Figure 2a, the surface of the specimen soaked in deionised water is relatively homogeneous and flat. At a concentration of 0.01 mol/L, several micropores are initiated, as shown in Figure 2b and 2c. A few micro fissures are initiated in the specimen soaked by H_2SO_4 solution.

When the anion concentration rises to 3 mol/L, as depicted in Figure 2d and 2e, a microcrack is observed in Cl^- solution. In SO_4^{2-} solutions, both microcracks and micropores increase in size and quantity. Additionally, the roughness and the fractal dimension of the fragments also increase with the concentration.

Furthermore, there is no significant change in the permeability of the granite, which remains around 0.002 mD. Combined with the X-ray diffraction analysis, certain anti-corrosion minerals in the granite have dense structures and low permeability, such as mica, quartz, feldspar, etc. The sheet structure also effectively prevents liquid infiltration. It explains the minimal effects of acid and anion corrosion on the microstructure of granite.

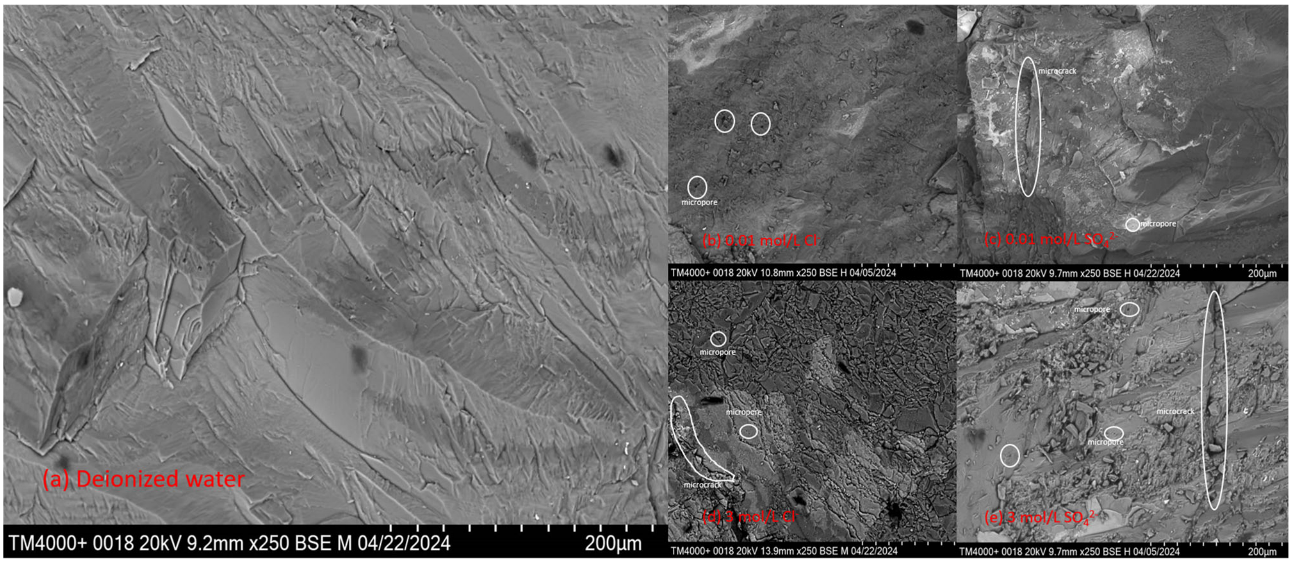


FIG 2 – SEM images of granite fragments soaked in NaCl and Na_2SO_4 solutions.

CONCLUSIONS

The experimental study shows that the sulfate ions and chloride ions do not significantly affect the mechanical and micro properties of the granite, as well as in acid conditions.

- The strength of the granite specimens decreases with the ion concentration. The effect of acid is more pronounced than anion on the strength and micro features of granite. Furthermore, SO_4^{2-} ion exhibits a greater impact than Cl^- ion.
- The deterioration level of the microstructure in the granite specimens increases with the anion concentration. Moreover, the low permeability also explains the corrosion resistance of granite.

REFERENCES

Fernando, W a M, Ilankoon, I M S K, Syed, T H and Yellishetty, M, 2018. Challenges and opportunities in the removal of sulphate ions in contaminated mine water: A review, *Minerals Engineering,* 117:74–90.

Geng, W, Wang, J, Zhang, X, Huang, G, Li, L and Guo, S, 2023. Experimental study of pore structure and rock mechanical properties of tight sandstone after acid treatment, *Acta Geotechnica*.

Han, T, Chen, Y, Shi, J, Yu, C and He, M, 2013. Experimental study of mechanical characteristics of sandstone subjected to hydrochemical erosion, *Chinese Journal of Rock Mechanics and Engineering,* 32:3065–3072.

Huo, R, Liang, Y, Li, S, Miao, Z and Qiu, T, 2022. The damage mechanism and deterioration characteristics of acid-corroded sandstone: an experimental study, *Arabian Journal of Geosciences,* 15.

Qiao, L, Wang, Z and Huang, A, 2016. Alteration of Mesoscopic Properties and Mechanical Behavior of Sandstone Due to Hydro-Physical and Hydro-Chemical Effects, *Rock Mechanics and Rock Engineering,* 50:255–267.

Sun, Q, Zhang, H, Hu, J, Geng, J and Zhou, S, 2023. Damage mechanism of granite under subcritical water–rock interaction, *Environmental Earth Sciences,* 82.

Sustainable mining

Opportunities for rare earth element recovery from waste streams

J Al-Shdifat[1]*, K Clode*[2] *and S Daykin*[3]

1. Consultant, Isle Utilities, Sydney NSW 2000. Email: jihan.al-shdifat@isleutilities.com
2. Asia-Pacific Market Leader – Industry, Isle Utilities, Sydney NSW 2000. Email: karen.clode@isleutilities.com
3. Global Head of Mining, Isle Utilities, Sydney NSW 2000. Email: sean.daykin@isleutilities.com

INTRODUCTION

Planning for a circular economy allows for previously untapped market opportunities to be explored, resulting in new, innovative revenue generating opportunities, while also reducing environmental impacts. In particular, rare earth elements (REE) are in rising demand as they are key components of over 200 products across a wide range of applications (Xie *et al*, 2023) including renewable energy technologies. There is a geographical disparity in deposits, with China being the top producer, generating 70 per cent of global production in 2022 (Laboure, 2023). This single dominating source has created supply chain concentration and hence supply risks for other nations, providing a driver for finding alternative sources, such as mine-influenced water (MIW) and tailings.

In this study, Isle presents a robust due diligence methodology for undertaking a global horizon scan into REE recovery technology, for a large mining company, from tailings decant water on a specific site. Previous studies of the tailings decant water at this site had shown potentially significant concentrations of both heavy and light REE, but challenges such as high flow, very low pH and high concentrations of iron had previously made recovery unfeasible.

Due to these challenges, the horizon scan focused on technologies that had the potential for selective recovery, despite the challenges with water quality, and considered a range of Technology Readiness Levels (TRLs). This included an adsorption-based process that has the potential to selectively separate individual REE, and a polymer based selective flocculation technology.

METHODOLOGY

Isle conducted an independent technology scan of available solutions for the recovery of rare earth elements, leveraging its technology database and a global network of start-ups, universities and research consortia to scout for solutions. This resulted in a longlist with technologies with a wide range of TRLs above 4/5. The technologies that were investigated consisted of biotic active and passive (eg redox reactions, biosorption, biooxidation) and abiotic active (eg adsorption-based processes, selective precipitation, flocculation, IEX, membrane treatment processes) technologies.

Following a review of the longlist, an evaluation framework was co-designed with key stakeholders to discuss the technologies in more detail, and during this process the most promising options were prioritised for further investigation. An overview of the methodology is shown in Figure 1.

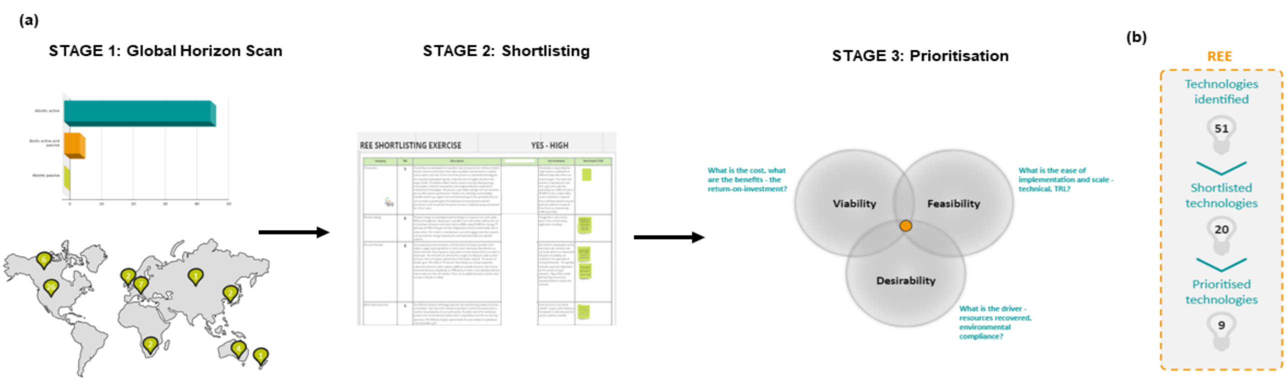


FIG 1 – Methodology overview.

SOLUTION IDENTIFICATION

The shortlisted technologies underwent techno-economic assessments to test the alignment of technologies with end user requirements. This matrix was used to filter down and shortlist technologies using three 'lenses' that describe an aspect of the technology's development. These three lenses were technical feasibility, economic viability, and desirability:

1. **Technical feasibility**: The feasibility lens provides context on the technology's treatment capacity per volume of water treated and identifies risks such as contaminants that mask or interfere with recovery and consumables. Scalability and integration with current operations are also tested.
2. **Economic viability**: The economic viability lens provides context on capital and operational costs, cash flows and return on investment to facilitate the raising of capital and allow stakeholders to make informed decisions.
3. **Desirability**: The desirability lens provides context on the REE resources recovered by the treatment process specifically on the purity and form of recovered REE, as well as other non-REE resources that are recovered by the treatment process. This lens also explores integration factors that may impact the operations of the mine site such as handling and disposal of waste flows and sludge produced by the process, upstream and downstream processes to complete the treatment train.

Isle reached out to prioritised technologies to carry out full due diligence on the providers and make an assessment according to the three lenses.

PRIORITISED TECHNOLOGIES

The following section outlines the technology landscape for REE recovery technologies determined through the above process.

1. **Overall TRL**: REE recovery technologies encompass a wide TRL spectrum. It has been observed that mature technologies have developed REE-selective mediums and processes that are based on established principles such as membrane filtration, flocculation, the use of binding polymers and ligands, as well as dialysis and ion exchange. Earlier stage technologies include the enhancement of traditional approaches using novel membrane materials and media that amplify physical and biological separation.
2. **REE recovery profile**: REE is commonly recovered as a concentrate (as part of a pregnant leach solution) in its oxide, chloride, sulfate or carbonate form. The purity depends on the approach for recovery and post-processing techniques and typically ranges between 5–95 per cent. Apart from REE, most technologies are able to recover metals such as Al, Fe and Cu.
3. **Operational integration**: Upstream processing techniques (mainly pre-filtration) to remove suspended solids, salts, or potentially competing or fouling species present in the water is typically required to make the REE recovery process more feasible. Downstream, metal recovery and reagent recycling processes may be applied to enable a fully circular solution. Jr jwlnsl%yjhmstqtlnjx%ymfy%kjfyzwj%f%wtgzxy%xjqjhyn{j%uwthjxx%fwj%qjxx%qpjq~%yt%wjvznwj%zuxywjfr% uwj2ywjfyr jsy%gzy%js{nwtsr jsyfq%inxhmfwlj%wjvznwjr jsyx%r jfs%it|sxywjfr%yjhmstqtlnjx%|nqq%xynqq% sjji%hts{jsyntsfq%ywjfyr jsy3

CONCLUSIONS AND NEXT STEPS

This study has mapped out the current technological landscape for REE recovery in tailings decant water and identified selective adsorption and flocculation as the most plausible techniques for immediate implementation. Trials are required to validate the insights of the evaluation in a manner that minimises technical and financial risks. The trial methodology should incorporate realistic, reasonable and robust success criteria to manage vendor expectations and site requirements at the same time identifying quantifiable performance indicators which is paramount to ensure a credible validation of a technology's fit to the project site. Assessments such as these are crucial in advancing the technology and connecting the solutions to the end users such that the supply chains of critical minerals and REEs can be expanded to support the global energy transition.

REFERENCES

Laboure, M, 2023. Rare earths – a powerful attraction [online]. Available from: <https://flow.db.com/trade-finance/rare-earths-a-powerful-attraction> [Accessed: 2 July 2024].

Xie, G, Guan, Q, Zhou, F, Yu, W, Yin, Z, Tang, H, Zhang, Z and Chi, R, 2023. A Critical Review of the Enhanced Recovery of Rare Earth Elements from Phosphogypsum, *Molecules*, 28(17):6284.

Blue Mining, a holistic approach that integrates circular economy

F Apollo[1], A Binder[2], M Bothe-Fiekert[3], O Langefeld[4] and S Nowosad[5]

1. Clausthal University of Technology, Clausthal-Zellerfeld 38678, Germany. Email: florence.apollo@tu-clausthal.de
2. Clausthal University of Technology, Clausthal-Zellerfeld 38678, Germany. Email: angela.binder@tu-clausthal.de
3. Clausthal University of Technology, Clausthal-Zellerfeld 38678, Germany. Email: mareike.bothe-fiekert@tu-clausthal.de
4. Professor, Clausthal University of Technology, Clausthal-Zellerfeld 38678, Germany. Email: oliver.langefeld@tu-clausthal.de
5. Clausthal University of Technology, Clausthal-Zellerfeld 38678, Germany. Email: sandra.nowosad@tu-clausthal.de

INTRODUCTION

The mining industry faces complex and urgent challenges driven by an increasing demand for raw materials, and a socially demanding globalised world. The extraction of primary raw materials is today more important than ever as one of the cornerstones towards a sustainable future since the increasing demand for the raw materials required for the energy transition. In the last three years, leading countries as USA, China, Canada, Australia, and the European Union (EU) have developed and adopted strategies to enhance domestic extraction capabilities, diversifying sources, fostering innovation in recycling, and promoting international collaboration related to critical raw materials. On 2022, the Inflation Reduction Act was signed into law in the USA, in June 2023, the Australian Critical Minerals Strategy 2023–2030 was published and in March 2024, the Council of the EU adopted the European Critical Raw Materials Act. On the other hand, raw materials extraction is facing higher environmental and safety standards and regulations, as well as scrutiny from the broader public. Regrettable environmental accidents as tailing dam failures or acid mine drainage occurrences have led to a general distrust of mining activities leaving mining companies with the dual imperative of increasing output while implementing sustainability, decarbonisation, and circularity as a core value in their production processes.

This challenging environment offers the opportunity to enhance ‘blue mining’ (BM) as a sustainable holistic approach that integrates the principles needed to plan sustainable, reliable, and responsible mines for today’s and future generations by implementing the principles of circular economy (CE). This requires a fundamental shift from the traditional linear economy approach to a sustainable, circular economy strategy. At its essence, BM encapsulates four crucial aspects – energy, ergonomics, water, and circularity and integrates these four aspects into integrative mine planning, defining clear goals and objectives from the ‘blueprint’ of a mine towards a beneficial post-mining activity. Its implementation can lead to maximisation of resources beyond the life of the extractive mine and sustainable use of materials by integrating the principles of circular economy and multi-use mine, see Figure 1. These concepts complement and recognise the need to minimise environmental and social impacts while advancing economic development. Finally, this contribution explains the requirements and challenges of moving from linear to dynamic planning approaches under the BM concept. This way, BM stands as an approach that can contribute to the mining industry receiving necessary approvals and support from society leading to a long-term transformation of the industry’s image.

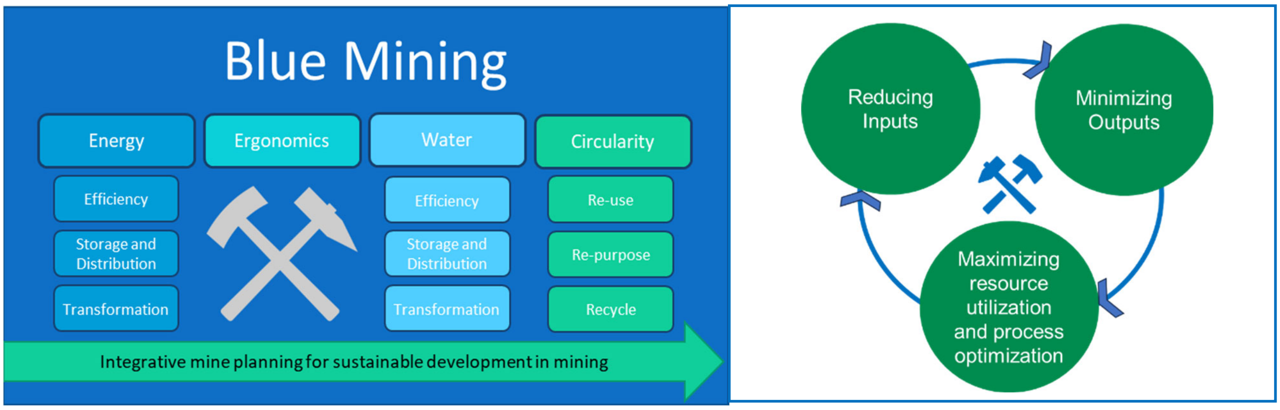


FIG 1 – The four aspects of Blue Mining (left) and the principles of Integrative Mine planning in the framework of Blue Mining (right) (modified after Bothe-Fiekert *et al*, 2023; Langefeld and Binder, 2022; Nowosad, Bothe-Fiekert and Langefeld, 2023).

BLUE MINING

Blue mining is a concept developed by the Institute of Mining of Clausthal University of Technology (CUT). The term 'blue mining' was inspired by the definition of the blue footprint or, from the German, 'Blaupause' which stands for very early stages in planning, which was adopted to represent responsible mining, thought from the 'blueprint' of a mine. In general, BM describes mines that are sustainable, energy-efficient, and ergonomic as an operation that: operates in an energy-efficient and ergonomic manner, pursues full automation; and supports sustainability by promoting the continuous use of mine sites during and after extraction (Kellner *et al,* 2013).

Moreover, the integration of this concept in mine planning is supported by three stages. In the first stage, different opportunities considering the three aspects of BM are identified and evaluated according to the project inherent situation. Then, synergies and conflicts of the interaction of the selected opportunity are identified. Finally, in the third stage, the detailed plan for integration is developed and assessed maximising synergies and minimising the conflicts that might occur (Langefeld and Binder, 2023). Integrating these principles into the early stages of mining requires a fundamental redesign of mine planning strategies towards an integrative mine planning (IMP) approach. The concept of multi-use mines along BM is consistent with the central goal of the CE to use energy but also further resources and products repetitive times throughout their life cycle rather than disposing of them after a single use. Converting mines into multifunctional facilities during and after the production phase helps to promote resource efficiency and thus supports the core objective of circularity. Experiences gathered in the integration of BM in research projects at CUT proved the relevance of IMP for the realisation of economic secondary utilisation of mined underground infrastructure. Moreover, IMP recognised post-mining as an integral phase in the life cycle of a mining project as it delineates the future economic and social development of the region. Figure 2 displays how the ability to influence the impact of the decisions before significant capital expenditure is high at early stages of a mining project and decreases over time while the data availability and quality increases as mining takes place. Therefore, IMP, advocates to integrate a circular approach from the blueprint of the mine to help mining companies optimise production and minimise their impact. Considering the impacts of all elements and processes, planners can identify opportunities and forms to optimise their usage in mining and guarantee the necessary data for future assessments is collected before, during and after the closure phase. Without proper planning, resources may be allocated inefficiently, leading to waste and reduced productivity even in some cases, wasting resources and unnecessarily increasing its carbon footprint. Evaluating only energy as input, different sources of energy interact within a mining operation – generally a mix of fossil fuels, compressed air, and electricity. Depending on the type of operation, one type of energy source has a higher demand than the others. Traditional and ongoing operations have a higher demand on fossil fuels meanwhile modern operations, can have a higher demand of electricity. Either way, scope 1 and 2 emissions are generated. To better manage emission generation, in IMP, energy efficiency, storage, distribution and transformation is integrated as an interactive goal since phase 1 and 2 of the life cycle of a mining project extending this step to the four aspects of BM.

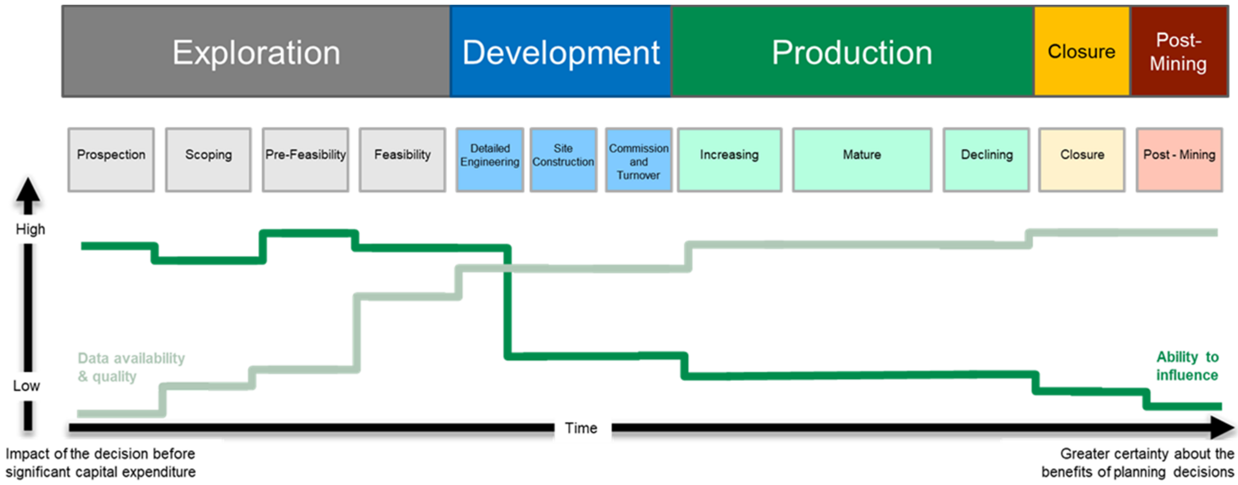


FIG 2 – Life cycle of a mining project in the framework of Blue Mining against the ability to influence the impact of the decisions before significant capital expenditure and the data availability and quality through time (modified after Bothe-Fiekert *et al*, 2023; Minviro Ltd and Shah, 2024; Nowosad, Bothe-Fiekert and Langefeld, 2023).

BM represents a promising approach to lead the mining industry into a more sustainable and efficient future. The concept supports the goals of the circular economy, as it aims to promote resource efficiency, reuse resources several times over, and at the same time focus on environmental and social aspects. Finally, moving from linear to dynamic planning approaches requires close collaboration with government agencies and consideration of environmental constraints. This is necessary to ensure that the mining industry receives the necessary approvals and support to successfully implement the new approaches.

REFERENCES

Bothe-Fiekert, M, Binder, A, Nowosad, S, Apollo, F and Langefeld, O, 2023. Lifecycle of Mine Water, *Yearbook of Sustainable Smart Mining and Energy 2022 – Technical, Economic and Legal Framework* (eds: W Frenz and A Preuße), vol 2 (Springer-Verlag: Berlin).

Kellner, M, Agasty, A, Clausen, E, Langefeld, O and Swanson, J G, 2013. Blue Mining – The future of Mining, Initial Considerations for under-ground pump storage plants, in *23rd World Mining Congress 2013* (Verlag: X-CD Technologies Inc.: Montreal, Canada).

Langefeld, O and Binder, A, 2022. Blue Mining, *Yearbook of Sustainable Smart Mining and Energy 2021 – Technical, Economic and Legal Framework* (eds: W Frenz and A Preuße), vol 2 (Springer-Verlag: Berlin). https://doi.org/10.1007/978-3-030-84315-1_13

Minviro Ltd and Shah, R, 2024. EU Regulations – The importance of quantifying upstream environmental impacts for battery end users, GMG Kiruna Forum 2024 (Global Mining Guidelines, Sweden).

Nowosad, S, Bothe-Fiekert, M and Langefeld, O, 2023. Blue Mining Strategically Integrates Circular Economy: Blue Mining setzt strategisch auf die Kreislaufwirtschaft, *Mining Report Glückauf*, 159(6):581–593.

PMAP – smart and sustainable *in situ* treatment of mine wastewater and critical metals recovery technology

M Barkh[1] and F X Spachtholz[2]

1. Founder and President, PMAP Mine Water Corp., Richmond, BC V6V 2N8, Canada. Email: mohsenb@pmap.ca
2. Professor (honorary) for Mine Planning at TU Clausthal, Germany; Chairman of the Board, President and CEO Baymag Inc., Calgary, AB T2W 4Y1, Canada. Email: franz.spachtholz@baymag.com

ABSTRACT

The mining industry faces significant environmental challenges in managing tailing ponds and wastewater treatment, including the risk of contaminated water, breaches of tailing dams, and energy-intensive treatment processes. Traditional methods involve pumping water to secondary treatment facilities for neutralisation, which is costly and poses operational and environmental risks.

In response to these challenges, the Professional Mine Water Action Plan (PMAP) introduces a revolutionary approach that combines cutting-edge AI technology and environmentally friendly reagents for *in situ* neutralisation of acidic wastewater. PMAP leverages magnesium-based slow-release reagents and AI-driven intelligent dispensing systems to optimise treatment processes within the tailing pond itself.

The unmanned smart dispensing vessel (USDV) conducts bathymetry to gather data on water quality and hydrography, allowing the system to determine the appropriate reagent quantity and injection strategy. This approach transforms the tailing pond into virtual reaction columns, enabling individual and simultaneous water treatment while optimising efficiency.

PMAP's novel reagent demonstrates exceptional efficacy in removing critical metals like cobalt, nickel, and copper, as well as reducing harmful metals such as mercury and manganese to undetectable concentrations. Unlike traditional lime-based treatments, PMAP's reagent prevents gypsum formation and reduces waste volume significantly, improving reagent utilisation and solid waste handling.

Furthermore, PMAP technology offers benefits beyond environmental stewardship. By reducing water treatment costs and improving resource management, it enhances operational efficiency and aligns with broader corporate sustainability goals. Additionally, PMAP expedites permitting processes by eliminating the need for traditional water treatment infrastructure and mitigating risks associated with hazardous reagent transportation.

Integrating PMAP as a pre-treatment for existing lime facilities provides further benefits, including optimisation of treatment operations, reduced reagent consumption, and the recovery of valuable metals from generated sludges.

Overall, PMAP represents a groundbreaking advancement in mining wastewater management, showcasing the transformative potential of AI and environmentally friendly solutions to foster sustainable and responsible mining practices globally. Its inaugural project in the Yukon Territory aims to demonstrate its capability to remove contaminants from mine water, paving the way for widespread adoption in the industry.

INTRODUCTION

Tailing ponds, integral to the mining industry, serve as repositories for waste materials generated during mining operations. Despite their utility, these engineered structures pose formidable environmental challenges. The untreated water within these ponds harbours a cocktail of heavy metals, chemicals, and sediments, presenting a grave risk to both environmental integrity and human health. The consequences of this contamination ripple through ecosystems, manifesting as water pollution, acid mine drainage, and toxicity to aquatic life. Moreover, the long-distance transport of contaminants exacerbates these issues, posing threats to regions far beyond the immediate vicinity of mining sites (Morgenstern, Vick and Van Zyl, 2015; McMahen and Hughes, 2016; Rotta *et al,* 2020; Franks *et al,* 2021). Equally concerning are the human health risks associated with exposure to these pollutants, ranging from neurological disorders to cancer and reproductive issues.

Addressing the multifaceted challenges posed by tailing ponds demands the deployment of sophisticated treatment technologies capable of efficiently and effectively mitigating environmental and health risks. Traditional methods, such as active treatment systems, are plagued by several issues that hinder their efficiency and effectiveness. One major challenge is the design malfunction due to the reliance on limited and non-representative sample water. This often leads to schedule delays and budget overruns as the initial design assumptions prove inaccurate. Additionally, traditional treatment processes involve exorbitant capital and operating costs, substantial energy consumption, and the necessity for skilled labour. The use of hazardous neutralisation reagents like lime and sodium hydroxide introduces further risks, encompassing transport, storage, and handling. Estimating the total volume of water in a tailing pond is challenging and often inaccurate, impacting treatment planning and execution. Moreover, traditional treatment processes lack adaptability to water quality fluctuations caused by natural events such as rain, snowfall, and evaporation, resulting in suboptimal treatment outcomes. Overdosing of reagents and subsequent pH overshooting are also common problems, creating compliance issues and further environmental harm.

Active treatment systems also face several disadvantages. Besides high capital and operating expenditures (CapEx and OpEx) the equipment maintenance cost is relatively high due to scaling. The high pH needed to remove metals may cause other metals such as aluminium, to become remobilised. Additionally, they generate a high volume of chemically complex and unstable sludge. This sludge is low-density and gelatinous, making it difficult and expensive to handle. Furthermore, the sludges generally have no commercial value, and the reclamation of metals from them is uneconomic (Brown, Barley and Wood, 2007).

The Professional Mine Action Plan (PMAP) Technology offers a revolutionary approach to tailing pond treatment by integrating advanced technological solutions and environmentally friendly methods. This innovative approach combines environmental friendliness, cost-effectiveness, and operational efficiency. Utilising an unmanned smart dispensing vessel (USDV), PMAP technology distributes a green slow-release magnesium-based neutralisation reagent into tailing ponds, treating them *in situ* with enhanced efficiency and safety. PMAP aims to transform the treatment landscape by providing an *in situ* solution that effectively treats contaminated water while minimising environmental risks in the event of a dam failure (Morgenstern, Vick and Van Zyl, 2015; McMahen and Hughes, 2016; Rotta *et al,* 2020; Franks *et al,* 2021). The core of PMAP technology includes a patent-pending non-hazardous neutralisation reagent (Barkh, 2023a) formula and an AI-based dispenser that measures water quantity and quality to inject the precise amount of reagent needed. This approach enhances treatment effectiveness and offers significant operational, environmental, and economic benefits.

PMAP TECHNOLOGY

PMAP technology encompasses a system utilising an unmanned smart dispensing vessel (USDV) for *in situ* tailing pond treatment through the distribution of an environmentally friendly, slow-release neutralisation reagent. It is founded on two main pillars:

1. A slow-release, non-hazardous, and eco-friendly neutralisation reagent formulation.
2. An AI-powered dispenser that gauges water quantity and quality to precisely inject the necessary neutralisation reagent.

A brief description of the technology pillars are as follows.

Slow-release, non-hazardous neutralisation reagent

The slow-release reagent is a magnesium-based formula that is non-hazardous and designed to neutralise contaminants in the tailing pond over time. The other components of the formula are aimed at other contaminants and increase reagent efficiency while supporting suspended solids removal before completing the treatment process. This approach, due to the slow-release nature of the reagent, eliminates both reactor tanks and mixing requirements for the neutralisation process and significantly reduces energy consumption. The use of the nonhazardous reagent minimises the immediate impact on the environment and enhances the safety and effectiveness of the reaction in a controlled environment.

AI-based dispenser

The optimum performance of the slow-release reagent depends on the precise injection of the required amount of the reagent at each injection point. Therefore, proper usage of the (AI-based) unmanned smart dispensing vessel (UDSV) plays a crucial role in PMAP technology. The USDV accurately measures the water's quantity and quality at each measuring point, allowing for the precise injection of the required neutralisation reagent. This precision ensures optimal treatment and minimises waste, making the process more efficient and cost-effective.

The two main pillars of technology, as illustrated in Figure 1, work in perfect harmony through a four-step process to provide the most efficient treatment option for tailing pond neutralisation. The main activities in the technology steps are listed below.

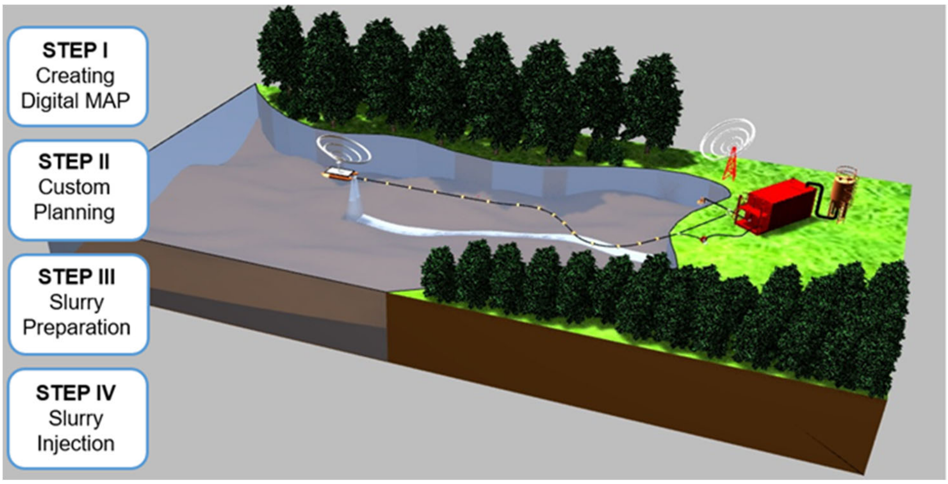


FIG 1 – Schematic of PMAP water treatment technology.

I – Creating a digital twin of the pond

The first step involves creating a 3D model (digital twin) of the tailing pond. The digital twin will connect the geographical coordination of each location of the pond to the quality of the water at the same location. This process creates a multidimensional digital map with detailed information about the pond's physical and chemical characteristics, which is essential for planning and optimisation.

II – Custom planning based on digital twin information and optimisation

Using the information from the digital twin, a custom plan would be developed for *in situ* pond water treatment. The plan would be optimised based on the treatment target and environmental parameters to ensure the most effective treatment strategy, considering the unique conditions of the pond.

III – Slurry preparation

The next step involves preparing the slurry, which includes the neutralisation reagent. The amount of required neutralisation reagent and other elements in the formula is determined and confirmed by bench scale tests. The physical and chemical characteristics of the slurry are carefully formulated to match the specifications required for effective treatment.

IV – Slurry injection according to the digital plan

Finally, the slurry, with an iterative process, is injected into the pond according to the digital plan. The AI-based dispenser ensures that the injection is precise and controlled, optimising the treatment process. The inline measurement of the water quality parameters after each iteration by the AI dispenser allows for continuous monitoring and correction of the neutralisation reaction at each injection point.

AN IN-DEPTH ANALYSIS OF PMAP REAGENT PERFORMANCE

The green and nonhazardous PMAP reagent is a combination of magnesium oxide, natural polymers, and other essential minerals and organics designed to neutralise and treat acidic mine water. The presence of magnesium oxide in the reagent imparts a buffering property that prevents the pH of the treated water from rising above 9.5, regardless of the amount of injected reagent. The magnesium salt in the PMAP formula begins introducing hydroxide ions into the water by forming magnesium hydroxide at any pH below 9.5. These hydroxide ions react with heavy metal ions in the water, producing insoluble metal hydroxides and neutralising the pH of the mine water.

The formation of insoluble metal hydroxides withdraws hydroxide ions from the aquatic environment, creating additional demand for hydroxide ions. This demand disrupts the equilibrium between dissolved hydroxide ions and magnesium salts, prompting the release of more hydroxide ions. The cycle of releasing hydroxide ions by magnesium salt and their consumption by insoluble heavy metal hydroxides continues at a pH below 9.5, as long as there is an adequate supply of magnesium salt, heavy metals, and time to reach equilibrium in the water. Since the removal of heavy metals and other contaminants is the primary objective of the treatment, the only factors available to manage the neutralisation reaction are the amount of injected PMAP reagent and the pond retention time.

The impact of reaction time and reagent dosage was extensively investigated for different concentrations of a wide variety of metals such as copper, nickel, cadmium, and others. Figure 2 illustrates an example of the removal efficiency of 2.5 g/L and 20 g/L of the PMAP reagent for mine water with a high concentration of nickel (4150 mg/L) over time (Barkh, 2023b). The use of 2.5 g/L of the PMAP reagent could only remove less than 20 per cent of the nickel, regardless of extended reaction time. In contrast, 20 g/L of the reagent showed continuous improvement in removal efficiency over time, with the initial removal efficiency of 37 per cent at day five increasing to 67 per cent after 20 days without any change in reaction conditions.

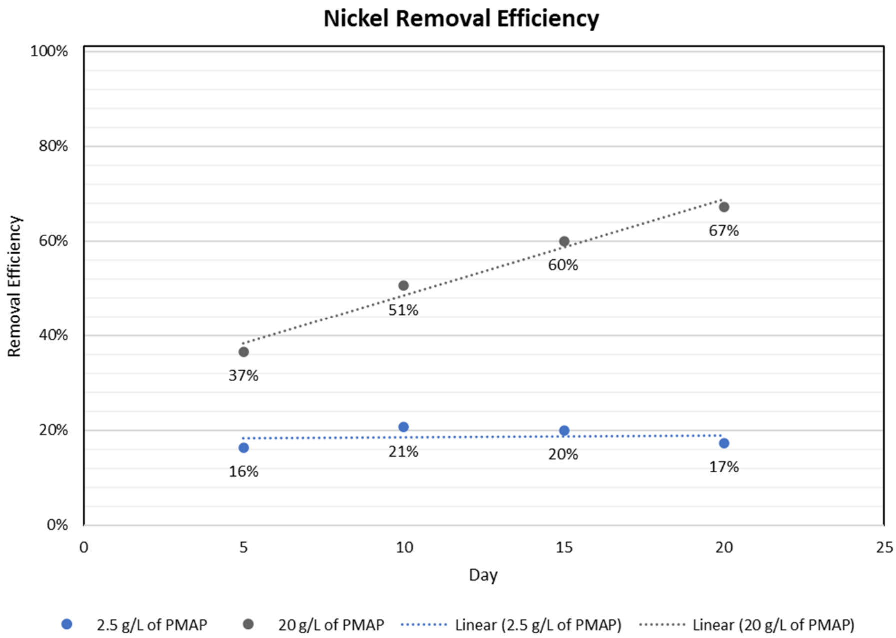


FIG 2 – Nickel removal efficiency by PMAP reagent at different dosages and time.

This test shows that using a small amount of reagent will break the hydroxide ion cycle in the water and control the progress of the treatment process over a long period. Meanwhile, the treatment process can be carried on by time if a sufficient amount of reagent is injected initially. In this case, the long hydraulic retention time of the pond could work in favour of the treatment process and improve the overall efficiency of the treatment process.

The PMAP technology, due to its unique slow-release property, showed success in removing heavy metals in a wide range of concentrations. For example, Figure 3 illustrates the treatment results for refinery wastewater with a low concentration of mercury (0.0433 μg/L) to achieve the treatment target of an undetectable concentration (<0.005 µg/L) of mercury (Barkh, 2024). The conducted tests present using only 0.5 g/L of the PMAP reagent over five days can achieve the treatment target without any mixing or additional post-treatment process.

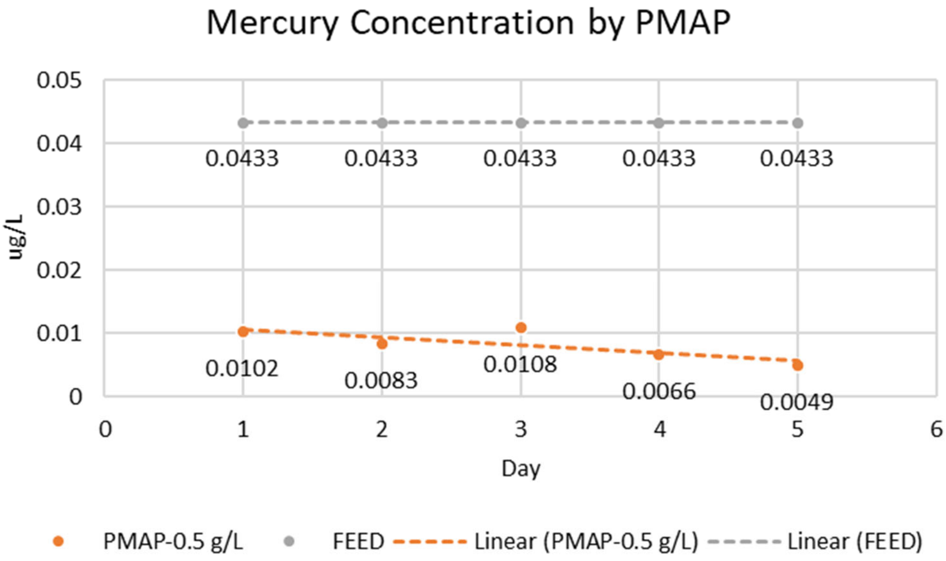


FIG 3 – Mercury removal to an undetectable level by PMAP technology.

Since many old mines own a lime treatment facility as their water treatment process, it was important to understand the potential use of the PMAP technology as pre-treatment in front of the lime operation. Figure 4 illustrates the utilisation of PMAP technology as pre-treatment for an existing lime facility.

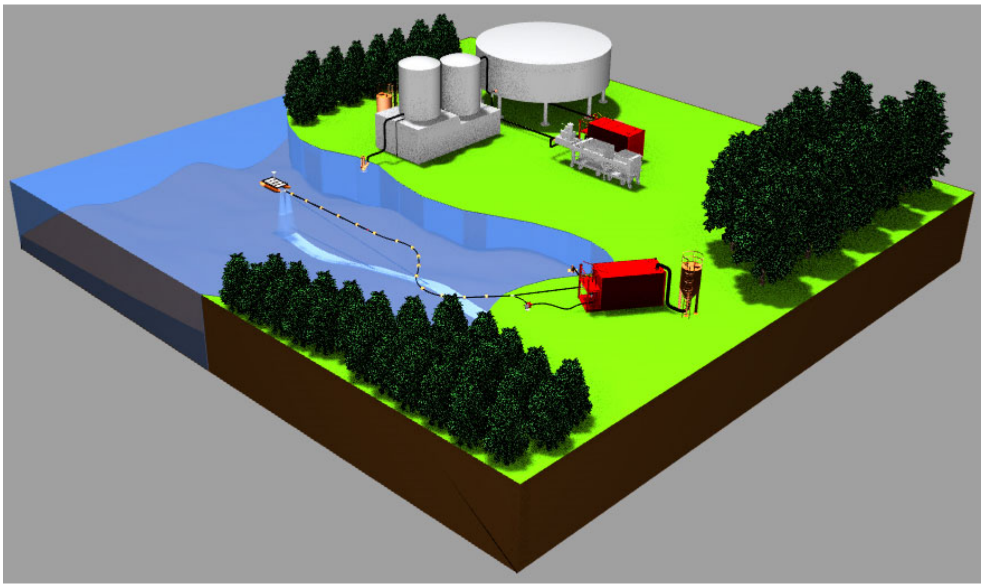


FIG 4 – Using PMAP technology as lime pre-treatment.

The PMAP reagent, due to the use of magnesium salts, prevents gypsum formation by introducing dissolved magnesium ions into the water. Therefore, adding the PMAP reagent to the mine water in the pond not only reduces lime consumption by increasing the pH of the water but also improves lime utilisation by averting the formation of the protective (inactivating) gypsum layer around the lime particles. Due to this action, a lower consumption of the lime reagent and a reduction in the overall reagent consumption was expected. Figure 5 presents the overall reagent consumption for a treatment train including PMAP technology as pond water pre-treatment (conditioning) followed by a lime process to produce dischargeable water at pH 9. The horizontal axis in the graph represents the amount of injected PMAP reagent 20 days before treating the overflow by lime (Barkh, 2023b).

The required amount of lime to produce treated water at pH 9 was 13.4 g/L in a traditional lime treatment process. However, injecting only 5 g/L of the PMAP reagent reduces the lime consumption to 5.5 g/L and provides an overall reagent consumption of 10.5 g/L. The use of a two-stage treatment reduces the lime consumption by 58 per cent and the overall reagent consumption by 20 per cent.

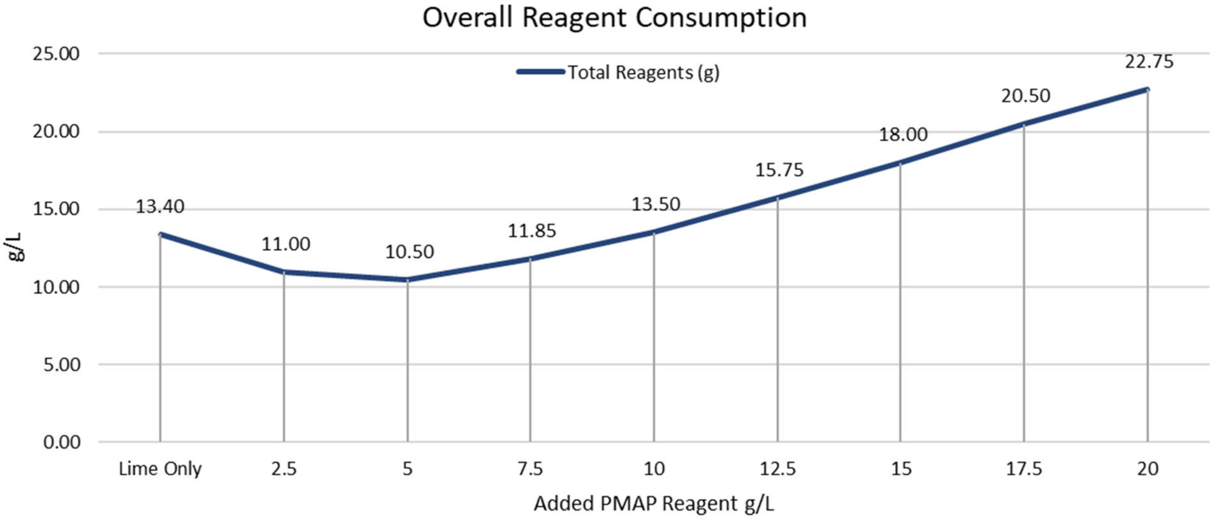


FIG 5 – Overall reagent consumption reduction after PMAP pre-treatment.

Since the insufficient injection of the PMAP reagent could remove selected metals without reducing the concentration of other dissolved metals, this process could produce sludge with a high percentage of a selected metal (eg copper) in the pond while the high concentration of other metals (eg nickel) would precipitate in the lime sludge. The sludge generated with both processes would be gypsum-free due to the presence of dissolved magnesium ions in the water, which prevents gypsum formation.

THE INNOVATIONS AND IMPACTS OF AI

The incorporation of AI in PMAP technology opens up numerous possibilities for enhancing the treatment process such as:

Multidimensional mapping

AI technology transforms the tailing pond into thousands or millions of reaction columns, effectively creating a digital twin of the pond. Figure 6 visualises the concept of converting the tailings pond into a network of side-by-side water columns. This mapping provides a detailed spatial understanding of the pond’s composition, enabling more precise and targeted treatment.

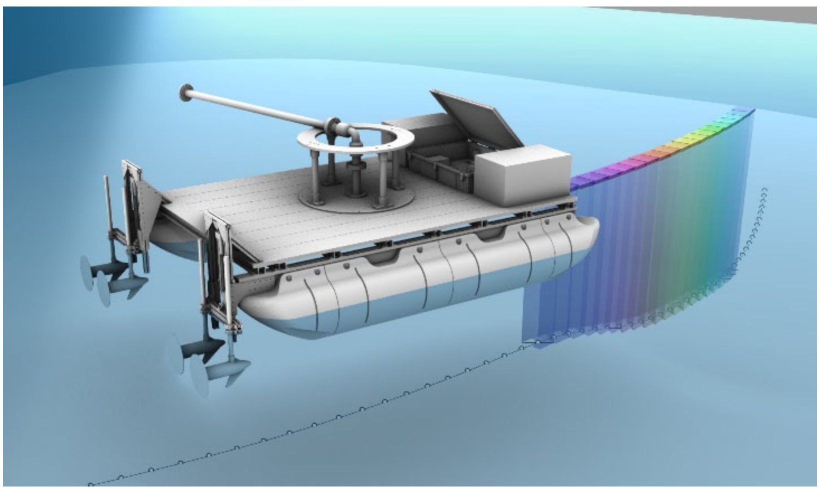


FIG 6 – AI Utilisation converts tailing pond to thousand reaction columns.

Reaction progress measurement

With AI, the progress of the neutralisation reactions within each column can be measured in real time. This capability allows for the continuous monitoring of the treatment process and includes the impact of the surrounding environment (columns) on the treatment progress, ensuring that adjustments can be made promptly to maintain optimal conditions.

Instantaneous analysis and adjustment

Based on the real-time data collected, AI analyses the reaction progress instantaneously. This rapid analysis enables the system to make immediate adjustments to the treatment process, such as modifying the quantity and quality of the injected neutralisation reagent to ensure effective treatment.

Controlled reaction conditions

AI controls the reaction conditions by adjusting the parameters of the neutralisation reagent injection such as the solid percentage of the slurry and injection flow rate. By fine-tuning these conditions, AI ensures that the reactions occur in a controlled manner, preventing issues such as pH overshooting or the formation of unwanted by-products like gypsum.

Optimised iterations

AI determines the number of required treatment iterations for each column based on real-time data. This optimisation ensures that the treatment process is both effective and efficient, reducing the overall time and resources required for complete neutralisation.

Operating parameters management

AI sets the operating parameters for the entire treatment system, including the mix tank, pumps, and other equipment. By managing these parameters, AI ensures that the system operates at peak efficiency, minimising energy consumption and wear on equipment.

Strategic decision-making

AI is capable of making strategic decisions about the treatment process, such as determining the optimal solid percentage of the slurry and the best intervals between treatment iterations. This strategic planning enhances the overall efficiency and effectiveness of the treatment process.

Selective precipitation

AI optimises the treatment process for the selective precipitation of target metals. This capability allows for the recovery of valuable metals from the tailing pond, turning a potential environmental liability into an economic asset.

BENEFITS OF USING PMAP TECHNOLOGY

Operational safety

The operational safety of PMAP technology is significantly enhanced by several key factors. First, the elimination of hazardous reagents greatly reduces the associated safety risks. The use of a non-hazardous magnesium-based neutralisation reagent minimises the potential for harmful chemical reactions on-site and during the transportation of the reagent. Additionally, the technology significantly reduces the number of required labourers, as much of the process is automated. This reduction in manpower not only decreases the risk of human error but also lowers the likelihood of workplace accidents. Furthermore, PMAP technology, as an *in situ* treatment, prevents the transportation of large volumes of contaminated water, which reduces the risk of spills and leaks during transport. By treating the entire body of the water in the pond, the technology also minimises the risk of contaminated water overflowing from the tailing pond, thereby protecting the surrounding environment.

GHG emission reduction

PMAP technology contributes to a significant reduction in greenhouse gas (GHG) emissions. The *in situ* treatment process reduces the need for transferring large volumes of water, which in turn lowers fuel consumption. This reduction in fuel usage directly translates to fewer emissions. Additionally, the technology reduces the need for extensive equipment fabrication and installation, both of which are energy-intensive processes. The lower carbon footprint of the neutralisation reagent further contributes to GHG emission reductions. In addition, due to the high utilisation rate of the reagent in the PMAP technology, the overall need for transporting neutralisation reagents on-site is reduced significantly. Overall, the use of PMAP technology represents a more sustainable approach to tailing pond treatment, aligning with global efforts to combat climate change.

Cost reduction

In terms of cost reduction, PMAP technology offers substantial savings on both capital and operating expenses. The need for specialised equipment such as reactor tanks, clarifiers, and lime preparation units is minimised, which reduces initial capital investments. The automated nature of the technology reduces the reliance on skilled labour, leading to lower operating costs. Due to the non-hazardous nature of the reagent, the need for secondary containment and a special storage facility for hazardous material is eliminated. Additionally, the optimisation capabilities of AI ensure that resources are used efficiently, further reducing operational expenses. By minimising waste and maximising the efficiency of the treatment process, PMAP technology also lowers the costs associated with waste handling and disposal.

Valuable metals recovery

One of the significant economic benefits of PMAP technology is the potential for valuable metals recovery. The precise injection of the neutralisation reagent allows for selective precipitation of valuable metals in the pond while the other contaminant remains dissolved in the water for a polishing (secondary) treatment by lime or other treatment technologies. The selective precipitation capabilities of the AI-based system allow for the extraction of valuable metals from the tailing pond. This recovery not only offsets the costs of the treatment process but can also provide a source of revenue. By turning waste into a resource, PMAP technology offers a compelling financial incentive for its adoption.

Comprehensive process advantages

PMAP technology offers a range of advantages that go beyond operational and environmental benefits. The technology reduces the amount of required equipment, skilled workers, and sludge volume, leading to lower capital, operating, and waste handling costs. It eliminates transportation risks, operational risks, and uncertainties related to water quality. By preventing issues such as pH overshooting, gypsum formation, and contaminants remobilisation, PMAP technology ensures a more stable and predictable treatment process. Additionally, the real-time operation control provided by AI allows for immediate adjustments and optimisations, ensuring that the treatment process remains efficient and effective.

CONCLUSION

The challenges posed by tailing ponds in the mining industry necessitate innovative and effective treatment solutions. Traditional methods, while useful, often fall short due to their high costs, inflexibility, and reliance on hazardous reagents. The Professional Mine Water Action Plan (PMAP) technology offers a transformative approach by integrating advanced, environmentally friendly methods with operational efficiency. Through the use of an unmanned smart dispensing vessel (USDV) and a slow-release, non-hazardous magnesium-based reagent, PMAP technology provides an efficient *in situ* treatment solution. This approach not only addresses the contamination in tailing ponds but also minimises environmental risks and operational costs. The incorporation of AI technology further enhances the precision and effectiveness of the treatment process, ensuring optimal reagent use and continuous monitoring. PMAP technology represents a significant advancement in tailing pond treatment, offering substantial environmental, economic, and operational benefits while paving the way for safer and more sustainable mining practices.

ACKNOWLEDGEMENTS

The author extends sincere gratitude to both teams of PMAP and Baymag Inc for their unwavering support throughout the technology development and R&D phase. Special appreciation is reserved for the shareholders of Baymag, the Refratechnik group of companies, for their invaluable support.

REFERENCES

Barkh, M, 2023a. Solid formulations for neutralizing acidic tailings ponds and methods of neutralizing acidic tailings ponds, International Patent Application PCT Patent No, PCT/CA2023/051364.

Barkh, M, 2023b. Investigation of Metals Removal Selectivity by PMAP Regaent, ReportLR 340-R1.Vancouver.

Barkh, M, 2024. Investigation of Ultra Low Mercury Removal by PMAP Reagent, Richmond.

Brown, M, Barley, B and Wood, H, 2007. *Minewater Treatment: Technology, Application and Policy* (IWA Publishing).

Franks, D M, Stringer, M, Torres-Cruz, L A, Baker, E, Valenta, R, Thygesen, K, Matthews, A, Howchin, J and Barrie, S, 2021. Tailings facility disclosures reveal stability risks, *Scientific Reports*, 11(1):5353.

McMahen, K and Hughes, C, 2016. Mount polley mine August 2014 tailings dam embankment breach response and approach to remediation, in Proceedings British Columbia Mine Reclamation Symposium.

Morgenstern, N R, Vick, S G and Van Zyl, D, 2015. Report on Mount Polley tailings storage facility breach, Report of Independent Expert Engineering Investigation and Review Panel to Province of British Columbia.

Rotta, L H S, Alcântara, E, Park, E, Negri, R G, Lin, Y N, Bernardo, N, Mendes, T S G and Souza Filho, C R, 2020. The 2019 Brumadinho tailings dam collapse: Possible cause and impacts of the worst human and environmental disaster in Brazil, *International Journal of Applied Earth Observation and Geoinformation*, 90:102119.

Australia's hydrogen export in the form of embedded mineral derivatives

G Burge[1], M Haider Ali Khan[2] and R Daiyan[3]

1. Chemical Engineering Student, The University of New South Wales, Sydney NSW 2052. Email: gabi.burge@outlook.com
2. Post Graduate Research Fellow, School of Minerals and Energy Resources Engineering, The University of New South Wales, Sydney NSW 2052. Email: muhammadhaiderali.khan@unsw.edu.au
3. Scientia Senior Lecturer, School of Minerals and Energy Resources Engineering, The University of New South Wales, Sydney NSW 2052. Email: r.daiyan@unsw.edu.au

ABSTRACT

Australia's mineral and metal exports have a substantial carbon footprint, twice that of its domestic emissions, mainly due to fossil-fuel-dependent downstream processes like processing into secondary metals and their transport. The country's vast renewable energy and low-carbon hydrogen potential offer a promising alternative to mitigate this impact. These resources can be leveraged to displace fossil fuel use and become embedded into the metals value chain. Ultimately, it will yield 'Green Metals' that can be scaled to reduce the environmental footprint and provide an avenue for Australia's vast green resources to be embedded (incorporated during production and supply) in green metals that can be exported. One potential green metal is copper, which is in great demand and likely to drive global decarbonisation through renewable electrification due to its role as an energy conductor. Given that Australia is a large producer and exporter of copper, this paper provides a techno-economic model of the copper value and applies it to Queensland (a hub of Australia's copper production) as a case study. The results show that under incumbent hydrogen (A$8/kg) and renewable energy costs, the cost of green copper would be A$9704/t (~10 per cent higher than current copper costs). Further analysis revealed that the cost of hydrogen is a major cost driver; therefore, if the cost of hydrogen can be reduced to A$2/kg (a 2030 target of the Australian government), the cost of green copper would become competitive. Furthermore, if a carbon pricing regime ($54–79/kg$CO_2$) is introduced, green copper would become competitive at a hydrogen cost of A$3/kg. Altogether, these findings provide insights for a future green copper export opportunity in Australia. Additionally, as the next step, the model can be extended to include other metals and released as an open-source resource for assessing global green metal opportunities.

INTRODUCTION

Australia has an abundance of the renewable energy resources required for producing green hydrogen (Bruce *et al*, 2018). Global demand for green hydrogen as a decarbonisation vector is increasing, giving Australia the opportunity to become a world leader in its production and export. However, the export supply chains and mechanisms are not yet established, and technical and economic challenges are faced in effectively distributing green hydrogen to meet the ready international demand.

Australia also has rich mineral resources and exports large volumes of critical minerals such as iron ore, aluminium, and copper. These exports contribute significantly to Australia's economy and support hundreds of thousands of jobs across their supply chains (Department of Industry Science and Resources, 2022). They are also important commodities for building renewable technologies such as electric vehicle batteries, solar panels, and power transmission infrastructure. Mineral resources will be vital in the global net-zero energy transition and are predicted to experience significant increases in demand. Global demand for copper is expected to double to 50 Mt by 2050 (International Copper Association, 2023).

In addition to the pressure to increase production, the sector is also facing pressure to decarbonise its value chains. The minerals sector is a significant contributor to carbon emissions through its use of fossil fuels and consumption of electricity. In 2021, domestic mining and minerals processing released ~52 Mt of direct CO_2-e into the atmosphere, representing 11 per cent of Australia's total emissions (Department of Climate Change Energy the Environment and Water (DCCEEW), 2023b).

These domestic emissions are just a fraction of the emissions resulting from downstream processing of Australian minerals. The scope 3 emissions of Australian iron ore are estimated at 900 Mt, which is nearly double Australia's domestic emissions from all sectors combined (Phillips, 2023). It has been recognised that carbon emissions are a primary cause of climate change, and government regulations are increasingly imposing emissions caps (eg Safeguard Mechanism) and import taxes (eg EU ETS) with carbon pricing mechanisms to drive emissions reductions and investment in low carbon practices and technology. In addition, there is also market pressure from green technology companies who demand verified low-carbon minerals for their product manufacture.

It has been identified that green hydrogen could be used as an alternative to fossil fuels in the minerals industry (Röben *et al*, 2021). This opportunity for hydrogen embedment in Australian mineral exports is two-fold. Decarbonisation of the minerals sector will safeguard the export security of Australian minerals to emissions-conscious markets and ensure a robust transition for the Australian mineral industry into a net zero future. By implementing green onshore processing of just 25 per cent of Australia's iron ore and alumina, global emissions would be reduced by 250 Mt per annum (Phillips, 2023). Additionally, the established export supply chains of the minerals industry will be a pathway for Australian hydrogen to enter the global market through value-added products. The techno-economic assessment of hydrogen embedment into minerals is still relatively under-studied. The focus of this work is on copper production, as it is relatively less well-studied in the Australian context and is a significant strategic mineral whose demand will increase in the coming decades (International Copper Association, 2023).

The International Copper Association identified alternative fuels, equipment electrification, decarbonised electricity and energy efficiency as key targets for reducing the Scope 1 and 2 emissions of copper production (International Copper Association, 2023). According to their estimates, 30–40 per cent of emissions can be reduced using green electricity, and the remaining 60–70 per cent can be reduced by increasing energy efficiency and alternative fuels. The installation of renewable energy generation and the use of PPAs are already reducing copper mining emissions worldwide. Copper mining company Grupo Mexico installed a 168 MW wind farm in Nuevo Leon that is expected to reduce 16 per cent of their Scope 2 emissions and 6 per cent of Scope 1 and 2 emissions (International Copper Association, 2023). The DeGrussa Solar Project by ARENA and Sandfire Resources implemented an off-grid solar powerplant with storage at the DeGrussa mine site to provide the majority of the operation's day-time energy (Climateworks Centre and Climate-KIC Australia, 2023). Renewable electricity can be used to charge battery electric vehicles (BEVs) and power grinding, flotation and electrolysis machinery. Electrolysis, in particular, requires direct current, which can be provided by solar PV with no conversion losses (Moreno-Leiva *et al*, 2020). However, because mining sites operate 24/7, the main challenge with using renewable energy is the intermittency of generation. Careful consideration will need to be given to the mix of renewable energy sources and the use of balancing technologies such as batteries or fuel conversion storage to maintain a consistent energy supply.

Renewable electricity supply to the mining site then incentivises the electrification of suitable equipment. For example, to replace underground vehicles, the Australian Industry Energy Transitions Initiative Pathways to Industrial Decarbonisation report identified that small underground battery electric vehicles (BEVs) are suitable and are already commercially available (Climateworks Centre and Climate-KIC Australia, 2023). The International Finance Corporation's Net Zero Roadmap for Copper and Nickel further explained that due to their lack of exhaust emissions, their use reduces the costs of underground ventilation, which has been the economic incentive for their deployment (International Finance Corporation, 2023).

For larger, above-ground hauling vehicles, the challenge of replacing diesel vehicles with BEVs is low battery energy density (Climateworks Centre and Climate-KIC Australia, 2023). The Rocky Mountain Institute has reported that alternative fuels, rather than electrification, are the more promising solution currently. Hydrogen fuel cell electric vehicles (FCEVs) are a possible technology; however, they identified the greatest barrier is the lack of infrastructure to support secure hydrogen supply chains (Muralidharan, Kirk and Koch Blank, 2019). The mining company Anglo American has proposed a system of on-site hydrogen generation which would eliminate their reliance on external supply chains. They propose that hydrogen would be generated from excess renewable energy and used to refuel haulage trucks (International Copper Association, 2023).

Smelting is another processing step that is unsuitable for full electrification. Fossil fuels such as natural gas and coke are required in furnaces to heat the copper concentrate to very high temperatures and cause oxidation reactions that remove impurities. Initial laboratory testing showed hydrogen had suitable properties to be used as an alternative fuel and reducing agent for copper refining (Degel *et al*, 2019). In addition, the techno-economic analysis found that copper refining's requirement for oxygen reactions makes hydrogen favourable, as oxygen is a by-product of electrolysis (Röben *et al*, 2021). In 2021, Aurubis, a metals processing facility and the largest global copper recycler, began conducting a pilot project to test the industrial-scale use of hydrogen as a natural gas replacement in their anode furnace (Aurubis, 2021). In 2023, they announced that approval had been granted to begin preparing their Hamburg site copper anode furnace for hydrogen use (Harings, 2023). Their goal is to reduce their annual carbon dioxide emission by 6200 t (Aurubis, 2021). Despite the promising technical properties of hydrogen, its high production, transmission and storage costs will be a barrier to its widespread use as an abatement option (International Copper Association, 2023). Röben *et al* (2021) reported that the additional costs of using hydrogen to decarbonise copper production could be up to 11 per cent of a company's revenue for the copper product. Therefore, it is important to identify and analyse the cost levers of hydrogen embedment to work towards reducing them.

The existing literature, in particular the work by Röben *et al* (2021), has investigated aspects of the processing stages of copper production. However, this work goes further by undertaking a holistic analysis of the entire value chain preceding export. In addition, no open-source models have been released that allow users to input unique process data, which is a key outcome of this work and an import resource for the mining industry.

METHOD

This study evaluates the levelised cost and emissions intensity of copper production using traditional fossil fuels in comparison to a green copper product. The boundary conditions of this analysis include onshore mining, processing and transport prior to international export within Australia. This boundary captures the areas of the copper supply chain where Australian renewable resources can be best used to achieve the aims of minerals decarbonisation. A techno-economic model was developed to carry out this study, and it is expected to be released as an open-source model.

Model development

The model was developed as an Excel worksheet that calculates the costs and emissions of a copper refining process based on parameters entered by a user, such as the processing site location, ore grade, smelting technology or transport method. It does this by quantifying the capacity of each processing stage and the type (eg electricity or fuel) and amount of energy consumed. From these values, the operating costs (OPEX), equipment costs (CAPEX) and emissions for the specified process are calculated. The OPEX and CAPEX are used to calculate a levelised cost of copper (LCOC).

To determine the capacity of each process, a material and energy balance was conducted for the entire copper refining value chain, from ore extraction and smelting to electrolytic refining. Figure 1 is a schematic of the processing stages, identifying the material inputs and outputs of each stage, current energy sources used in production and the chosen decarbonisation pathways.

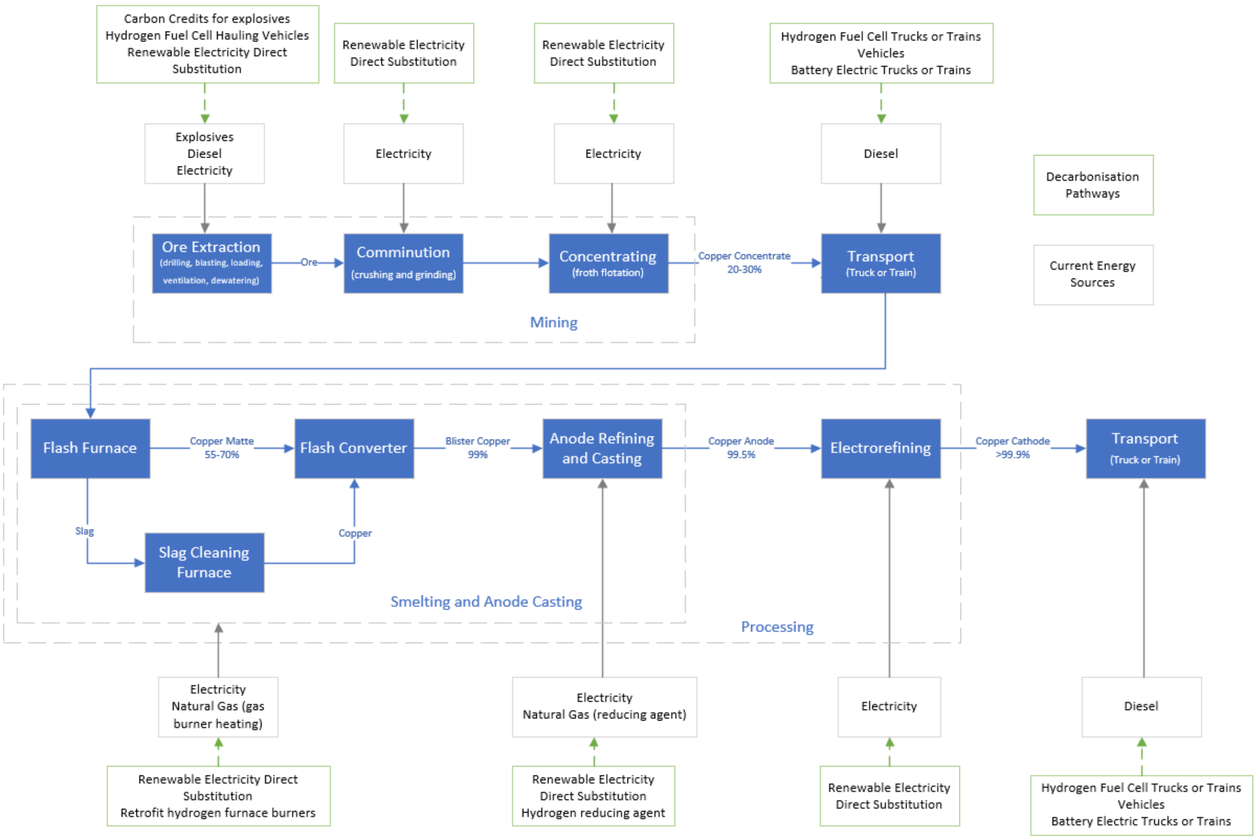


FIG 1 – Copper value chain schematic.

Mining

The mining stage consists of ore extraction, comminution and concentrating. These processes convert an ore of 1–2 per cent copper into a concentrated product of 20–30 per cent. The mass of concentrate able to be produced determines the modelled amount of energy and costs required for smelting. The resulting mass of concentrate is given by Equation 1.

$$Concentrate\ Mass = \frac{Ore\ Mass \times Ore\ Grade \times Recovery}{Concentrate\ Grade} \qquad (1)$$

Energy consumption is supplied to the model by the user as kWh or GJ on a per tonne basis of either ore or concentrate and multiplied through by the calculated mass. Hydrogen substitution for diesel in mining machinery was calculated to be the equivalent energy as required for doing work on a per mass basis.

Smelting and anode casting

The pyrometallurgical smelting process was chosen for the model as it uses fossil fuels for heating and reactions that can be substituted with hydrogen. This stage consists of several processes where the copper concentrate is reacted with first oxidants and then reductants to separate out impurities such as iron or silica. The mass of anode able to be produced determines the modelled amount of energy and costs required for electrorefining. The resulting mass of copper anode produced is given by Equation 2.

$$Copper\ Anode\ Mass = \frac{Concentrate\ Mass \times Concentrate\ Grade \times Recovery}{Copper\ Anode\ Grade} \qquad (2)$$

Much of the energy of the process is produced by exothermic oxidation reactions, however some natural gas is supplied for heating. Hydrogen substitution was calculated to be the equivalent energy required for heating on a per-mass basis.

The anode casting process uses natural gas as a reductant to react with copper oxide. The reaction is given by Equation 3.

$$Cu_2O + \frac{1}{4}CH_4 \rightarrow 2Cu + \frac{1}{4}CO_2 + \frac{1}{2}H_2O \qquad (3)$$

The same copper oxide chemical conversion can be achieved using hydrogen, as shown by Equation 4.

$$Cu_2O + H_2 \rightarrow 2Cu + H_2O \tag{4}$$

Based on a techno-economic study conducted for copper, it is assumed that complete conversion occurs for both reactions (Röben *et al*, 2021). This means that four times as many moles of hydrogen are required compared to natural gas. Hydrogen substitution was calculated based on this molar ratio.

Electrorefining

The electrorefining stage uses electricity and heat to purify the copper anode to the extremely high purity copper cathode. The resulting mass of copper cathode produced is given by Equation 5.

$$Copper\ Cathode\ Mass = \frac{Copper\ Anode\ Mass \times Copper\ Anode\ Grade \times Recovery}{Copper\ Cathode\ Grade} \tag{5}$$

Hydrogen substitution was calculated to be the equivalent energy as required for heating on a per mass basis.

Transport

Transport of copper derivatives is required to move material from processing areas on-site, between different sites and to the export port. Depending on the distance and available infrastructure this is either by train or truck. Hydrogen substitution was calculated to be the equivalent energy as required for the transport mode per mass of the load and distance travelled.

Levelised cost

The levelised cost of the final refined copper product is calculated using Equations 6 and 7. This method is based on a similar analysis conducted by (Bhaskar *et al*, 2022) for green steel.

$$LCOC = \frac{C_{capex} \times ACC + C_{opex}}{Annual\ Copper\ Production} \tag{6}$$

where:

$LCOC = Levelised\ Cost\ of\ Copper$

$C_{capex} = Total\ Capital\ Investment$

$C_{opex} = Annual\ Operational\ Cost$

$ACC\ =\ Capital\ Recovery\ Factor$

$$ACC = \frac{r \times (1+r)^n}{(1+r)^n - 1} \tag{7}$$

where:

$r = discount\ rate$

$n = plant\ life$

Emissions

The embedded emissions of grid electricity were automatically assigned based on the emissions factor at the location selected by the user in the tool. Data was obtained from the Department of Climate Change Energy the Environment and Water's (DCCEEW) National Greenhouse Accounts Factors Publication (DCCEEW, 2023a). Emissions were calculated using Equation 8.

$$Emissions\ = Electricity\ Consumption\ \times\ Emissions\ Factor \tag{8}$$

Fuels such as diesel and natural gas have scope 1 emissions that depend on their use eg combustion of diesel for freight train or truck transport or natural gas as either a heat source or as a reducing agent. Emissions factors were assigned by use case using factors from the Greenhouse Accounts Factors (DCCEEW, 2023a) and literature. Emissions were calculated using Equation 9.

$$Emissions = Energy\ Consumption \times Emissions\ Factor \quad (9)$$

Analysis scenario

Base case

A case study of an Australian copper production process was developed to use as a base case for this study. The case study was modelled on an existing mining and refining operation at Mt Isa and Townsville in Northern Queensland. At the time of developing the case study, Mt Isa was a major operation covering the value chain of this study. Figure 2 shows the site locations on a map with a description of the activities conducted at each. The current copper production pathway is heavily dependent on fossil fuels for vehicles, electricity, heat and chemical reactions. The Input parameters given below in Table 1 outline the fossil fuel requirements for each stage of copper production.

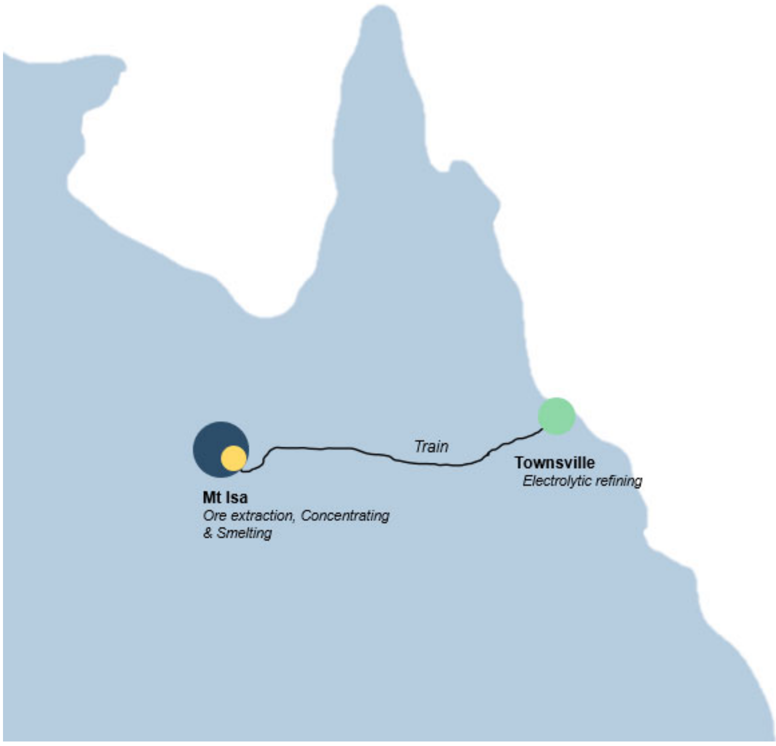


FIG 2 – Base Case site locations.

Base case input parameters

Table 1 provides the key input parameters for the Base Case. The inputs were determined from publicly available information about the existing mine operations and assumptions made by other researchers.

TABLE 1

Base case key input parameters.

Parameter	Value	Unit	Source
Mine site location	Queensland		Mt Isa mine site location
Mass of ore processed	18 912 550	t-ore	Ore basis to produce 300 000 t of refined copper cathode
Ore grade	1.8 per cent		(Norgate and Haque, 2010)
Crushing and grinding electricity consumption	18.5	kWh/t-ore	(Norgate and Haque, 2010)
Concentrate grade	27.3 per cent		(Norgate and Haque, 2010)
Concentrating electricity consumption	120	kWh/t-conc	7.5 kWh/t-ore (Norgate and Haque, 2010) = ~120 kWh/t-conc (for 27.3 per cent conc grade)
Concentrator fixed investment cost	22 581	A$/t-Cu	$USD (2019) 11 000/t-Cu (Schlesinger *et al*, 2022)
Copper anode grade	99.7 per cent		Mt Isa, Australia: 99.7 per cent (Glencore, 2023a)
Smelting natural gas consumption (heat)	3063	MJ/t-anode	Isasmelt Smelting/RHF Matte/Slag Settler + PS Converting (incl. steam credit): 3063 MJ/t-anode (Coursol and Mackey, 2010)
Anode refining and casting natural gas consumption (reducing)	6	Nm^3/t-anode	6 Nm^3/t-anode (Coursol and Mackey, 2010)
Smelter fixed investment cost	20 528	A$/t-Cu	$USD (2019) 10 000/t-Cu (Schlesinger *et al*, 2022)
Refinery site location	Queensland		Townsville Electrolyser (Glencore, 2023a)
Electricity consumption	350	kWh/t-cathode	350 kWh/t-Cu (Moreno-Leiva *et al*, 2020; Schlesinger *et al*, 2022)
Copper cathode grade	99.995 per cent		Townsville Electrolyser, Australia: 99.995 per cent (Glencore, 2023a)

It has been proposed that the fossil fuels used in the above process can be substituted with green energy sources such as hydrogen and renewable electricity. A scenario was modelled for a Green Copper Product which substitutes diesel and natural gas for hydrogen and uses renewable electricity and carbon credits to eliminate net carbon emissions of the primary production processes.

Green copper product

The levelised cost of a Green Copper product produced at the Base Case site using retrofitted equipment and renewable energy was modelled. Green hydrogen was modelled at A$8/kg, representing the lower of current ranges (Williamson, 2023). Renewable electricity was modelled at 0.075 A$/kWh, representing the mid-range for current PPA contracts.

The cost of green copper production technology for a commercial scale retrofit is difficult to reliably obtain for each piece of equipment (Delgado Sancho *et al*, 2017; Röben *et al*, 2021). Therefore, for this case study, the Green CAPEX was modelled as a percentage increase compared to the Base Case CAPEX costs. Looking at the green steel industry for comparison, it is known that the cost of H2-DRI steel is expected to be >30 per cent greater than BF-BOF plant (Venkataraman *et al*, 2022) and in 2023 there was an 11.6 per cent increase in capital expenditure for 20 companies due to investment in critical minerals and decarbonisation projects (GlobalData, 2023). Based on this it was assumed that the Green Copper CAPEX is 15 per cent higher than for the Base Case.

Values chosen for the annuity factors were based on similar techno-economic analysis conducted by (Bhaskar *et al*, 2022) for a green steel production process decarbonised with hydrogen in Norway. A discount rate of 10 per cent and a plant life of 25 years were modelled.

Economic analysis

Economic analysis was conducted to provide insight into the decarbonisation strategies and costs entailed by different economic scenarios. Of particular focus was understanding how hydrogen cost impacts the viability of using minerals as an export vector, and how carbon pricing impacts the competitiveness of green copper. Modelling was undertaken with a range of hydrogen and carbon credit prices predicted for 2030. Nine scenarios were developed to study the interactions between the different variables.

Economic analysis input parameters

The cost of green hydrogen is dependent on the cost of renewable electricity used to produce it (Longden *et al*, 2020), so for this economic analysis they are analysed as dependent variables. The data in Table 2 is based on analysis by researchers at ANU (Longden *et al*, 2020) who compiled cost estimates from the CSIRO and AEMO GenCost Report (Graham *et al*, 2021) and the CSIRO Hydrogen Roadmap (Bruce *et al*, 2018) to estimate production costs of green hydrogen as a function of electricity price in Australia. The range of $2–4/kg for hydrogen was chosen, including the target price of $2/kg and cases where this target is not met (Chang, 2022). The carbon price was adopted from the Australian Carbon Credit Unit Costs predictions (EY, 2023). Combining the three hydrogen price variables and the three carbon credit price variables gave nine possible scenarios for the economic landscape in 2030. Table 2 defines each scenario.

TABLE 2

Economic analysis scenario inputs.

Scenario	Electricity price (A$/MWh)	Hydrogen price (A$/kg)	Carbon credit price (A$/ACCU)
1	25	2	28
2	25	2	54
3	25	2	79
4	45	3	28
5	45	3	54
6	45	3	79
7	65	4	28
8	65	4	54
9	65	4	79

Each scenario was modelled with all other input parameters from the case study held constant.

RESULTS AND DISCUSSION

Base case

The Levelised Cost of Copper (LCOC) at the export port for the Base Case was found to be A$8912/t. The key driver of this cost was CAPEX. This is lower than reported prices in industry of delivered copper at A$12 700/t (Glencore, 2023b) and for futures contracts on the London Metal Exchange at

A$12 600 (London Metal Exchange, 2023). Sensitivity analysis was conducted to identify the drivers of this discrepancy.

It was found that CAPEX and discount rate have a much more significant impact on the calculated LCOC than OPEX. Increasing the OPEX alone could not improve the model to reflect real copper prices. However, there is a positive relationship that highlights the scope for additional operating costs such as waste handling or labour to be included in the model.

Increasing the discount rate improves the model performance; however, rates higher than 12 per cent (equivalent to a 20 per cent increase in the variable) are not generally used for Australian mining projects. A study of 100 mining projects found an average discount rate of 7.18 per cent, with the lowest rate of 5 per cent and highest of 12 per cent (Ovalle, 2020). Of these projects, three Australian mining projects had a 0 per cent country risk premium and average discount rates of 8.08 per cent (Ovalle, 2020). Therefore, it is recommended that the discount rate is not increased.

CAPEX had the most significant impact on the LCOC, and it is reasonable to expect that it would have been underestimated in the model. An increase of 50 per cent in CAPEX brings the LCOC up to the actual price of A$12 700/t. Therefore, it is recommended that both the CAPEX and OPEX assumptions should be revised to improve the tool. However, the model is still useful as a comparison tool for hydrogen embedment, as the additional costs would be similar across both the Base Case copper and the Green Copper product.

The emissions of the Base Case were found to be 3422 kg-CO_2/t-Cu. This is consistent with the value of 3800 kg-CO_2/t-Cu calculated in a life cycle assessment by the International Copper Association (Copper Alliance, 2021). Analysis of the emissions sources reveals that 99 per cent of the emissions of the process can be abated with renewable electricity and green hydrogen. The remaining 1 per cent are the embedded emissions from the production process of explosives used in ore extraction.

Green copper

The LCOC for the Green Copper Product was found to be A$9704/t-Cu. This is 9 per cent more expensive than the Base Case and represents an average increase in costs (over the plant lifetime) of A$238 million/a at a capacity of 300,00 t-Cu/annum. Due to the unabatable explosive emissions, this product's real emissions were 35 kg-CO_2/t-Cu, and the LCOC includes an operating cost of A$0.3 million/a in carbon credits to offset these.

The largest contributor to the OPEX was found to hydrogen, which made up 77 per cent of the total expenditure. This was followed by electricity at 24 per cent. This indicates that bringing down hydrogen price will be the most significant lever in reducing the levelised cost of green copper.

CAPEX was modelled as a percentage increase of the Base Case; therefore, specific equipment contributions cannot be analysed. There is also likely to be a higher error in this component of the LCOC due to the lack of publicly available information to support the assumed value. To quantify this, sensitivity analysis was conducted to understand how significantly the error in this value affects the LCOC. The results of this analysis highlight a significant implication for the industry regarding the capital costs to upgrade equipment to be compatible with renewable processing methods and fuels. For example, if the actual increase in CAPEX is 30 per cent rather than 15 per cent, then the LCOC would be A$1120/t-Cu, which is 12 per cent higher than as presented in the case study and even less economically viable. As with hydrogen OPEX, the cost of new technology and retrofitting will also be a significant lever for driving the price of Green Copper.

The results of the case study analysis showed that for the modelled Australian copper production process, Green Copper is not competitive with the fossil fuel derived copper product, even when carbon offsetting is applied. It was found that hydrogen price and the cost of capital are significant levers that affect the LCOC for Green Copper.

Economic analysis

Nine scenarios of varying green hydrogen and carbon credit prices and their impact on Green Copper LCOC were analysed using the model. The results are given graphically in Figure 3.

Figure 3 shows how sensitive the Green Copper LCOC is to hydrogen price. When hydrogen is priced at A$4/kg, the Green Copper product is significantly uncompetitive with the fossil fuel copper (Base Case) for all scenarios of carbon pricing. However, at A$3/kg, moderate (A$54/t-CO_2e) and high (A$79/t-$CO_2$e) carbon pricing scenarios push the fossil fuel product price above that for Green Copper.

Hydrogen priced at A$2/kg results in a Green Copper product that has the same LCOC as the Base Case and is highly competitive against the offset Base Case (ie with carbon credits applied). In this scenario, the hydrogen price is equivalent to A$15/GJ, which is comparable to natural gas (A$14.5/GJ) and significantly cheaper than diesel (A$54/GJ), making the product's energy expenditure competitive.

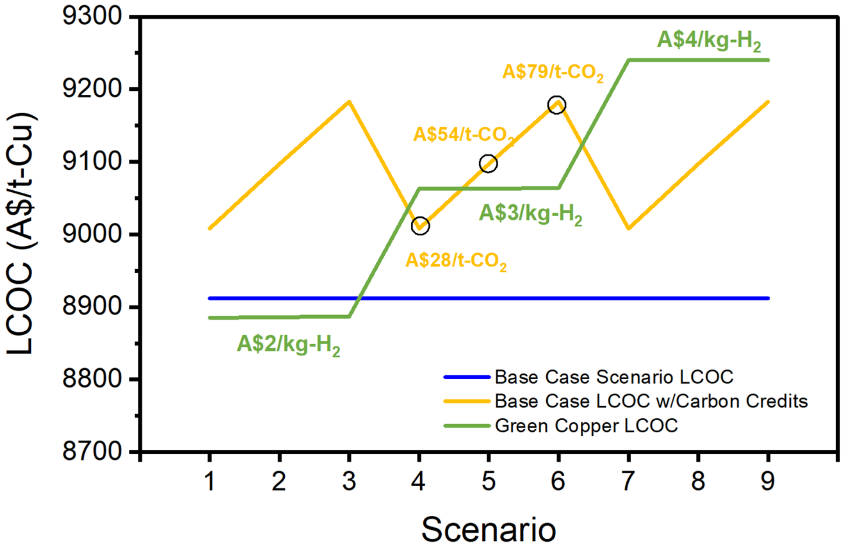


FIG 3 – Economic analysis results.

This economic analysis has identified that achieving a green hydrogen price of less than A$4/kg-$H_2$ will be a significant factor in ensuring that Green Copper can be produced at a competitive price. Hydrogen at A$3/kg-$H_2$ will be satisfactory in a regulatory environment of moderate to high carbon pricing (A$54–79/kg-$CO_2$), while at A$2/kg-H_2 the Green Copper is competitive regardless of carbon pricing policy. Further case studies and model validation will be required to substantiate these findings; however, it is promising that the hydrogen price identified aligns with Australia's target of A$2/kg-$H_2$ in the National Hydrogen Strategy (COAG Energy Council Hydrogen Working Group, 2019).

CONCLUSIONS

A techno-economic tool was developed and used to assess the factors affecting the export of Australian hydrogen in the form of embedded copper. A case study of a copper value chain in Queensland found that a fossil fuel derived product (The Base Case) has a LCOC of A$8912/t. In comparison, Green Copper produced with hydrogen at A$8/kg-$H_2$ has a levelised cost of A$9704/t. The Base Case copper price was validated against real copper prices, and it was identified that further work is required to improve the CAPEX and OPEX modelling to ensure the outputs of the tool align with these prices. However, the results are still useful for comparison, and it can be concluded that high hydrogen prices and the large capital expense required to retrofit or replace processing equipment to be compatible with hydrogen are key levers in the increased cost of Green Copper.

Economic analysis found that embedding Australian produced green hydrogen in mineral derivatives can be a viable economic pathway for export to the rest of the world if the hydrogen used by copper producers can be produced at A$2/kg-$H_2$. In a political landscape of moderate to high carbon pricing (A$54 to A$79/t-CO_2), hydrogen at A$3/kg-$H_2$ also becomes competitive.

The outcome of this work will be an open-source tool with an online interface that will allow stakeholders and other researchers to evaluate pathways for critical minerals producers to achieve net zero and foster further research in this area. The tool will be used to identify the cost drivers of decarbonisation, directing research to the most impactful areas.

REFERENCES

Bhaskar, A, Abhishek, R, Assadi, M and Somehesaraei, H N, 2022. Decarbonizing primary steel production: Techno-economic assessment of a hydrogen based green steel production plant in Norway, *Journal of Cleaner Production*, 350. https://doi.org/10.1016/j.jclepro.2022.131339

Aurubis, 2021. Aurubis: First copper anodes produced with hydrogen. Available from: <https://www.aurubis.com/en/media/press-releases/press-releases-2021/aurubis-first-copper-anodes-produced-with-hydrogen>

Bruce, S, Temminghoff, M, Hayward, J, Schmidt, E, Munnings, C, Palfreyman, D and Hartley, P, 2018. Australian National Hydrogen Roadmap, CSIRO, p 92. Available from: <www.csiro.au/en/research/environmental-impacts/fuels/hydrogen/hydrogen-roadmap>

Chang, A, 2022. Europe shifts investment to Australia's hydrogen energy, InfoLink Consulting. Available from: <https://www.infolink-group.com/energy-article/green-hydrogen-costs-in-australia-to-reduce-37-by-2030> [Accessed: 31 Oct 2023].

Climateworks Centre and Climate-KIC Australia, 2023. Pathways to industrial decarbonisation: Positioning Australian industry to prosper in a net zero global economy. Available from: <https://www.climateworkscentre.org/resource/pathways-to-industrial-decarbonisation-positioning-australian-industry-to-prosper-in-a-net-zero-global-economy/> [Accessed: 20 March 2023].

COAG Energy Council Hydrogen Working Group, 2019. Australia's National Hydrogen Strategy. Available from: <https://www.dcceew.gov.au/sites/default/files/documents/australias-national-hydrogen-strategy.pdf> [Accessed: 19 February 2023].

Copper Alliance, 2021. Copper Environmental Profile. Available from: <https://copperalliance.org/wp-content/uploads/2021/07/ICA-EnvironmentalProfileHESD-201803-FINAL-LOWRES-1.pdf> [Accessed: 17 Nov 2023].

Coursol, P and Mackey, P J, 2010. Energy Consumption in Copper Sulphide Smelting Proceedings of Copper, *Materials Science,* pp 649–668.

Degel, R, Lux, T, Hecker, E, Filzwieser, A, Krassnig, H J and Filzwieser, I, 2019. Innovative solutions in non-ferrous metals production, in *Proceedings of the 58th Annual Conference of Metallurgists (COM) Hosting the 10th International Copper Conference*.

Department of Climate Change Energy the Environment and Water (DCCEEW), 2023a. Australian National Greenhouse Accounts Factors. Available from: <https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-accounts-factors-2023>

Department of Climate Change Energy the Environment and Water (DCCEEW), 2023b. National Inventory by Economic Sector 2021. Available from: <https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-accounts-2021/national-inventory-by-economic-sector-2021>

Department of Industry Science and Resources, 2022. Resources and Energy Quarterly December 2022. Available from: <https://www.industry.gov.au/publications/resources-and-energy-quarterly-december-2022>

Delgado Sancho, L, Roudier, S, Farrell, F, Cusano, G and Rodrigo Gonzalo, M, 2017. Best available techniques (BAT) reference document for the non-ferrous metals industries – Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control). European Commission, Joint Research Centre. https://doi.org/doi/10.2760/8224

EY, 2023. Changing Gears: Australia's Carbon Market Outlook 2023. Available from: <https://info.ey.com/Australias-Carbon-Market-Outlook-2023.html>

Glencore, 2023b. Half-Year Production Report 2023, Baar. Available from: <https://www.glencore.com/.rest/api/v1/documents/static/26ae0436-7810-403e-b3b2-e069d77d1b36/GLEN_2023-H1_ProductionReport.pdf> [Accessed: 17 Nov 2023].

Glencore, 2023a. Copper Refineries Pty Ltd. Available from: <https://www.glencore.com.au/operations-and-projects/qld-metals/operations/copper-refineries> [Accessed: 3 Jul 2023].

GlobalData, 2023. Mining capital expenditure to rise by 12% across leading miners in 2023, Mining Technology. Available from: <https://www.mining-technology.com/comment/mining-capital-expenditure-2023/?cf-view> [Accessed: 31 Oct 2023].

Graham, P, Hayward, J, Foster, J and Havas, L, 2021. GenCost 2020–21: Final report Australia. Available from: <https://www.csiro.au/-/media/EF/Files/GenCost2020-21_FinalReport.pdf>

Harings, R, 2023. Speech by Annual General Meeting of Aurubis AG. Available from: <https://www.aurubis.com/en/dam/jcr:c29465ee-f1a3-4903-8c2f-1a1560c4668b/Aurubis_AGM>

International Copper Association, 2023. Copper—The Pathway to Net Zero. Available from: <https://internationalcopper.org/resource/copper-pathway-to-net-zero/> [Accessed: 3 February 2023].

International Finance Corporation, 2023. Net Zero Roadmap for Copper and Nickel Mining. Available from: <https://ccsi.columbia.edu/sites/default/files/content/docs/publications/ccsi-net-zero-roadmap-copper-nickel.pdf>

London Metal Exchange, 2023. LME Copper. Available from: <https://www.lme.com/en/metals/non-ferrous/lme-copper #Summary> [Accessed: 17 Nov 2023].

Longden, T, et al, , Jotzo, F, Prasad, M and Andrews, R, 2020. Green hydrogen production costs in Australia: implications of renewable energy and electrolyser costs, CCEP Working Paper. Available from: <https://iceds.anu.edu.au/files/2020%2009%2001%20-%20ZCEAP%20-%20CCEP%20Working%20Paper%20-%20Green%20hydrogen%20 production%20costs.pdf>

Moreno-Leiva, S, Haas, J, Junne, T, Valencia, F, Godin, H, Kracht, W, Nowak, W and Eltrop, L, 2020. Renewable energy in copper production: A review on systems design and methodological approaches, *Journal of Cleaner Production*, 246:118978. https://doi.org/10.1016/j.jclepro.2019.118978

Muralidharan, R, Kirk, T and Koch Blank, T, 2019. Pulling The Weight of Heavy Truck Decarbonization Exploring Pathways to Decarbonize Bulk Material Hauling in Mining. Available from: <https://rmi.org/insight/pulling-the-weight-of-heavy-truck-decarbonization/> [Accessed: 20 March 2023].

Norgate, T and Haque, N, 2010. Energy and greenhouse gas impacts of mining and mineral processing operations, *Journal of Cleaner Production*, 18(3):266–274. https://doi.org/10.1016/j.jclepro.2009.09.020

Ovalle, A, 2020. Analysis of the discount rate for mining projects, in *MassMin 2020: Proceedings of the Eighth International Conference and Exhibition on Mass Mining* (eds: R Castro, F Báez and K Suzuki), pp 1048–1064 (University of Chile: Santiago). https://doi.org/10.36487/ACG_repo/2063_76

Phillips, T, 2023. Green gold: A strategy to kickstart Australia's renewable industry future. Available from: <https://cpd.org.au/wp-content/uploads/2023/10/20230925-Green-gold-Report__.pdf>

Röben, F T C, Schöne, N, Bau, U, Reuter, M A, Dahmen, M and Bardow, A, 2021. Decarbonizing copper production by power-to-hydrogen: A techno-economic analysis, *Journal of Cleaner Production*, 306. https://doi.org/10.1016/j.jclepro.2021.127191

Schlesinger, M E, Sole, K C, Davenport, W G and Alvear Flores, G R F, 2022. *Extractive Metallurgy of Copper*, 6th edition (Oxford: Elsevier). Available from: <https://www.sciencedirect.com/book/9780128218754/extractive-metallurgy-of-copper> [Accessed: 20 Jun 2023].

Venkataraman, M, Csereklyei, Z, Aisbett, E, Rahbari, A, Jotzo, F, Lord, M and Pye, J, 2022. Zero-carbon steel production: The opportunities and role for Australia, *Energy Policy*, 163:112811. https://doi.org/10.1016/JE.NPOL.2022.112811

Williamson, R, 2023. "It's a start:" Forrest welcomes Australia's $2 billion hydrogen response to US plan, *Renew Economy*. Available from: <https://reneweconomy.com.au/its-a-start-forrest-welcomes-australias-2-billion-hydrogen-response-to-us-plan/> [Accessed: 22 November 2023].

Eco-efficiency of ANFO and bulk emulsion explosives application in Indonesian mining

R Heryadi[1] and H Utama[2]

1. Lecturer, Nusa Putra University, Sukabumi West Java 17132, Indonesia. Email: rudy.heryadi@breny.my.id
2. Junior Mining Manager, PT Indomuro Kencana, Murung Raya Central Kalimantan, Indonesia. Email: heru.utama@imkgold.co.id

ABSTRACT

The demand for environmentally friendly commercial explosives has increased globally due to concerns regarding environmentally friendly mining activities. Ammonium nitrate fuel oil (ANFO) and bulk emulsion explosives (BEE) are two kinds of civil explosives primarily used in coal and mineral mining in Indonesia. Indonesia is one of the leading countries in coal and mineral mining production and export, with abundant resources; therefore, the consumption of civil explosives such as ANFO and BEE is enormous. The selection and evaluation of commercial explosives are mostly done on the commercial and technical side, and no assessment is made based on environmental aspects. This preliminary study evaluates the economic value and environmental burden of greenhouse gas emissions produced by ANFO and BEE and determines which type of explosives is more environmentally friendly. The combination of environmental and economic indicators, eco-efficiency (E/E), was selected to investigate BEE's economic and environmental performance compared to ANFO. The life cycle of greenhouse gas emissions of BEE and AN was determined using previously available studies and simple calculations. The cost of the product or explosives was used to represent the economic value. The E/E results showed that environmental and economic sustainability could be enhanced using BEE.

INTRODUCTION

Blasting in the mining industry for coal, minerals, and quarries is needed, especially for breaking rocks to get the products. During the mining operation, caution is required during drilling and blasting operations. Blasting activities are preceded by drilling blastholes, filling explosives into the blastholes, and continuing with stemming, tie-up, and shot firing. Drilling and blasting activities must be carefully planned before the activity is conducted. One that needs to be considered carefully is the blasting pattern, but this is not the only factor; another important factor that needs to be considered is the selection of the explosives type used. Most types of explosives used in coal and mineral mining are ANFO (Ammonium Nitrate Fuel Oil) and Bulk Emulsion explosives (BEE), which both consist of Ammonium Nitrate and fuel oil as the main component (Nitrate explosives).

Bulk emulsion explosives (BEE) are primer-sensitive only if chemically gassed and sometimes with additional material such as glass micro balloon (Mahadevan, 2013). It contains 5–10 per cent fuel content and 90–95 per cent aqueous oxidiser (Ferreira, Freire and Ribeiro, 2015; Mishra *et al*, 2018). The density can be manipulated within the range of 0.92 g cm^{-3} to 1.15 g cm^{-3} to suit the blasting requirement (Mishra *et al*, 2018). BEE is usually formulated with an additional 30 per cent of AN and is called a 70–30 bulk blend. BEE works excellently in a wet blasthole due to its water resistance feature, is widely known for its high energy content compared to ANFO, and is suitable for medium to hard rock (Dhekne, Balakrishnan and Jade, 2020; Lee and Persson, 1990). The main disadvantages of BEE are its cost per unit and maintaining the exact height of charge in the blasthole; more BEE quantity is used since its density is higher than the ANFO (Ayat and Allen, 1988).

BEE can give better fragmentation when blasting as its energy content is higher than ANFO, generating more shock waves when the detonation reaction happens. Yudha, Sudarmono and Mukiat (2014) found that the BEE gives better fragmentation and digging time than ANFO, even if the pattern was extended and the same powder factor was utilised. In terms of economic value, the cost of BEE is higher than that of ANFO; However, the price of BEE is higher than ANFO. BEE has added value compared to ANFO, especially with its high energy level, pumpability, and water resistance. In terms of environmental burden, BEE can significantly reduce the burden on the environment when BEE is applied. The blast pattern can be extended, reducing the fuel needed to drill the blastholes and during charging operation (Yudha, Sudarmono and Mukiat, 2014). Besides the benefits of BEE when applied and the cost reduction through pattern extension, BEE displays less environmental burden than ANFO. As environmental issues are becoming a concern in the mining sector, selecting more environmentally friendly explosives is also critical; therefore, selecting BEE to replace ANFO must also consider the environmental aspect. One method to evaluate the benefit of products compared with similar products is calculating product eco-efficiency (E/E).

According to the World Business Council for Sustainable Development (WBCSD), E/E is defined as 'the provision of goods and services at competitive prices to satisfy human needs and bring quality to life, and progressively reduce ecological impacts and resource intensity throughout the life cycle up to a level that corresponds to the earth's carrying capacity' (Verfaillie and Bidwell, 2001). E/E indicator can be used as an evaluation indicator to determine the feasibility of a product economically and environmentally. E/E indicators were used in a study on the cultivation of rapeseed and sunflowers as raw biodiesel materials in Italy (Forleo *et al*, 2018). The method used in research by Forleo *et al* (2018) is to look for LCA and then for gross added value or economic value from rapeseed and sunflowers; then, the LCA and Economic data are used to look for E/E indicators. The final result is that rapeseed is more sustainable and economically profitable than sunflowers.

So far, there have been many discussions regarding comparisons between ANFO and BEE-type explosives, including technical comparisons through blasting results, fragmentation of blasting results, and theoretical economic calculations in using ANFO compared to BEE (Putra, Toha and Sudarmono, 2015; Widodo, Anwar and Syafitri, 2019; Yudha, Sudarmono and Mukiat, 2014). Although there have been several studies that have been carried out, studies that discuss comparisons between ANFO and BEE in terms of their environmental burden and measurement of their eco-efficiency have never been found; this study was conducted to provide comparisons in economic calculations as well as comparisons of environmental burden, especially its greenhouse gas emission as a result of the blasting activity. This study aims to find which type of explosives is more sustainable and environmentally friendly. A combination of environmental and economic indicators (E/E) was selected to investigate the performance of BEE compared to ANFO.

METHOD

E/E of BEE and ANFO can be found by first finding the economic value of BEE and ANFO, and further, the environmental burden of BEE and ANFO can be obtained from another study.

BEE and ANFO economic value

The Economic Value of BEE and ANFO is obtained based on the vendor quotation. The economic value of the ANFO and BEE was calculated in units of material blasted or bank cubic metres (bcm). The cost of BEE can be the same as that of ANFO by extending the blast pattern whenever BEE is used to replace ANFO. The blasthole diameter is 200 mm. Table 1 shows the parameters used for calculation.

TABLE 1

Parameter used for calculation of the explosives consumption.

Explosives geometry parameter	Unit	ANFO	BEE	Remark(s)
Blasthole diameter (h)	mm	200	200	standard blasthole diameter
Burden (B)	m	7.00	8.30	for 200 mm blasthole diamater, standard value for ANFO is 7 m
Spacing (S)	m	7.00	8.30	spacing assumed equal with the burden
Stemming (T)	m	4.00	4.00	
Subdrill (J)	m	0.00	0.00	no sub drill
Bench Height (H)	m	9.00	9.00	
Depth (L)	m	9.00	9.00	
Column charge length (PC)	m	5.00	5.00	column filled with explosives
AN Percentage	%	94.5	81	
Fuel Percentage	%	5.5	5.5	
Additional diesel fuel from the genset and boiler	Litre	28		The boiler consumed 20 L of fuel per ton emulsion blend, and the genset consumed 8 L of fuel per ton emulsion blend.
Fuel Ratio	L/t explosives	74	131	
Powder Factor (PF)	Kg/bcm	0.14	0.14	Explosives per bank cubic metre (bcm)

The typical cost of explosives per bcm material blasted in coal and mineral mines in Indonesia is between USD 0.45 and USD 0.60 per bcm (based on vendor quotation). For this E/E calculation, the value used is USD 0.45 per bcm. The volume of the material to be blasted is assumed to be 700 000 bcm of overburden, and the blast pattern for ANFO is Burden (B) = 6 m, spacing (S) = 7 m, and depth = 9 m. The blast pattern for BEE is B = 7 m; S = 8 m; and depth = 9 m. The blasthole diameter is 200 mm.

Greenhouse gas emission of BEE and ANFO

The life cycle emission of BEE and ANFO is calculated based on references provided for BEE and ANFO data. It is clear that either ANFO or BEE GHG emissions mainly come from the Ammonium Nitrate production, which gives 1.6 tons CO_2-eq emission per ton ANFO product used, while two other GHG emissions contributed by blasting operation and transportation of explosives from manufacturer to mine site depot and from mine site depot to blasting front. Blasting operation contributes 0.2 tons CO_2-eq per ton ANFO, and transportation contributes less than 0.1 CO_2-eq per ton ANFO (Climateleaders.org, 2020). The emission of diesel fuel consumed in boiler and genset can be calculated by using the correlation of the CO_2 produced per litres of diesel fuel consumed, which is 2.68 kg CO_2 per litre of diesel fuel (Pilkington, 2022).

Eco-efficiency (E/E) calculation

The E/E of a product is the ratio between the product's economic value and the environmental impact caused by the product (Huppes and Ishikawa, 2009). The formula to calculate efficiency is shown in Equation 1.

$$Product\ Eco - efficiency\ \frac{Economic\ Value\ (US\$)}{Greenhouse\ Gas\ Total\ Emission (kg\ CO2eq)} \tag{1}$$

The equation above conveys the relationship between economic feasibility results and analysis of the environmental burden. Eco-efficiency can also be carried out for one type of product with variations in changes analysed through sensitivity analysis (Burchart-Korol *et al*, 2016).

RESULT AND DISCUSSION

Based on the parameter in Table 1, the cost of the explosives per bcm per annum can be obtained. The cost is USD 3.78 million bcm^{-1} $year^{-1}$. This cost is the cost for blasting either by using BEE or ANFO. Table 2 shows the GHG emission per blasting that can be reduced per annum by using BEE compared to ANFO.

TABLE 2

GHG emission of BEE and ANFO.

Explosives type	Holes required per day	Explosives required (tons day^{-1})	AN content (AN + fuel oil only)	GHG emission (tons CO_2 eq day^{-1})	GHG emission (tons CO_2 eq $year^{-1}$)
ANFO	53	7079	7079	13.43	4939
BEE	37	6686	5843	11.10	4440
			Total GHG emission reduction		**499**

By extending the pattern, fewer holes drilled, and fewer explosives will be consumed per ton or cubic metre of material. The potential for GHG reduction can be calculated. By improving blast design (extension of pattern), GHG emissions can be reduced and positively contribute to climate change. By using bulk emulsion (consisting of AN, fuel oil, emulsifier, and water), only 81 per cent of AN, 5.5 per cent of fuel blend, and the remaining is water, around 14 per cent per ton of bulk emulsion blend (70:30). It can be ensured and calculated that the amount of the GHG life cycle emission is lesser than ANFO, and can be assumed only 86.5 per cent of GHG emissions when BEE used as an explosives to replace ANFO. The CO_2 generated is 0.007504 tons per ton emulsion blend.

It is evident that when BEE is used, and the blast pattern extended, less explosives, fuel, and drilling activity is conducted (Sigalingging, 2017; Yudha, Sudarmono and Mukiat, 2014); therefore, less GHG emission is also expected. The E/E of the BEE and ANFO is shown in Table 3.

TABLE 3

E/E of ANFO and BEE.

Parameter	ANFO	BEE
Economic value (million USD $year^{-1}$ bcm^{-1}) *	3.78	3.78
Life cycle GHG emissions (tons CO_2-eq/a)	13.43	11.10
Eco-efficiency (E/E)	0.28	0.34

The E/E indicator compares the sustainability performance of several products or processes by integrating economic and environmental sustainability aspects. The environmental sustainability aspect of explosives such as BEE and ANFO is assessed using the data of life cycle GHG emission analysis, and the economic sustainability aspect of bulk explosives is obtained using the economic indicator in this study is the cost of the explosives per bcm material blasted. The comparison in Table 3 shows that the use of BEE as a substitute for ANFO shows a higher E/E value when compared to the use of ANFO, where the higher the E/E value, the more eco-efficient is the product (BEE E/E = 0.34 and ANFO E/E = 0.28). The lower environmental burden or GHG emission causes the higher E/E value of BEE as a substitute for ANFO. If we refer to the E/E indicator, a more sustainable investment from both the economic value aspect and the environmental burden aspect is the utilisation of BEE compared to the utilisation of ANFO as the main explosives.

An E/E assessment can also be used to compare several variables that influence the economic feasibility of bulk explosives.

CONCLUSIONS

Evaluating the sustainability of the BEE using E/E indicators shows that BEE used as a substitute for ANFO in blasting operations is more eco-efficient than when ANFO is used as an explosive in coal and mineral mining. Despite the cost of the BEE and ANFO being the same, evaluation based on environmental factors combined with economic feasibility is important, especially when deciding which type of explosives can benefit technically and, at the same time, more environmentally friendly need to be executed. Furthermore, a more detailed study that asses the life cycle GHG emissions of BEE and ANFO in specific coal and mineral mining projects must be conducted to confirm this study on the E/E of BEE and ANFO in the coal and mineral mining industry.

REFERENCES

Ayat, M G and Allen, S G, 1988. Emulsions: The cutting-edge development in blasting agent technology-a method for economic comparison, *Mining Science and Technology*, 6(3):285–289. https://doi.org/10.1016/S0167-9031(88)90272-1

Burchart-Korol, D, Krawczyk, P, Czaplicka-Kolarz, K and Smoliński, A, 2016. Eco-efficiency of underground coal gasification (UCG) for electricity production, *Fuel*, 173:239–246. https://doi.org/10.1016/j.fuel.2016.01.019

Climateleaders.org, 2020. Improving Efficiency and Reducing GHG Emissions, ClimateLeaders.org. Available from: <https://www.climateleaders.org.au/case-studies/incitec-pivot-1/>

Dhekne, P Y, Balakrishnan, V and Jade, R K, 2020. Effect of Type of Explosive and Blast Hole Diameter on Boulder Count in Limestone Quarry Blasting, *Geotechnical and Geological Engineering*, 38(4):4091–4097. https://doi.org/10.1007/s10706-020-01280-y

Ferreira, C, Freire, F and Ribeiro, J, 2015. Life-cycle assessment of a civil explosive, *Journal of Cleaner Production*, 89:159–164. https://doi.org/10.1016/j.jclepro.2014.11.027

Forleo, M B, Palmieri, N, Suardi, A, Coaloa, D and Pari, L, 2018. The eco-efficiency of rapeseed and sunflower cultivation in Italy, Joining environmental and economic assessment, *Journal of Cleaner Production*, 172:3138–3153. https://doi.org/10.1016/j.jclepro.2017.11.094

Huppes, G and Ishikawa, M, 2009. Eco-efficiency guiding micro-level actions towards sustainability: Ten basic steps for analysis, *Ecological Economics*, 68(6):1687–1700. https://doi.org/10.1016/j.ecolecon.2009.01.007

Lee, J and Persson, P-A, 1990. Detonation Behavior of Emulsion Explosives, *Propellants, Explosives, Pyrotechnics*, 15(5):208–216. https://doi.org/10.1002/prep.19900150507

Mahadevan, E G, 2013. *Ammonium Nitrate Explosives For Civil Applications* (Wiley-VCH Verlag and Co, KGaA).

Mishra, A K, Rout, M, Singh, D R and Jana, S P, 2018. Influence of Gassing Agent and Density on Detonation Velocity of Bulk Emulsion Explosives, *Geotechnical and Geological Engineering*, 36(1):89–94. https://doi.org/10.1007/s10706-017-0308-7

Pilkington, B, 2022. Gasoline vs Diesel: Which is More Polluting? [online]. Available from: <https://www.azocleantech.com/article.aspx?ArticleID=1580>

Putra, I G, Toha, M T and Sudarmono, D, 2015. Batuan Menggunakan Bahan Peledak Anfo Dan Bulk Emulsion Pada Lapisan Interburden Pit 4500 Blok Selatan Pt . Pamapersada – Dahana (Persero) Jobsite Melak, Kalimantan Timur Blasting Geometry Evaluation Toward Rock Fragmentation Using Blasting Material an, *Jurnal Ilmu Teknik*, 3(2) [in Indonesian].

Sigalingging, A S P, 2017. Perbandingan Teknis dan Ekonomis pada Operasi Peledakan Cross Cut dalam Penggunaan Emulsion sebagai Pengganti Anfo pada Underground Big Gossan PT Freeport Indonesia, Tembagapura, Papua Comparison of the Technical and Economical on Blasting Operations Cr, *Prosiding Teknik Pertambangan*, 416–423 [in Indonesian].

Verfaillie, H and Bidwell, R, 2001. Measuring eco-efficiency — a guide to reporting company performance, report produced for the World Business Council for Sustainable Development. Available from: <https://www.gdrc.org/sustbiz/wbcsd.html>

Widodo, S, Anwar, H and Syafitri, N A, 2019. Comparative analysis of ANFO and emulsion application on overbreak and underbreak at blasting development activity in underground Deep Mill Level Zone (DMLZ) PT Freeport Indonesia, *IOP Conference Series*: *Earth and Environmental Science*, 279(1). https://doi.org/10.1088/1755-1315/279/1/012001

Yudha, N F, Sudarmono, D and Mukiat, 2014. Kajian Teknis Pemakaian Emulsion Sebagai Pengganti Anfo Pada Peledakan Lapisan Tanah Penutup Terhadap Produktivitas Hitachi Ex-2600 Pt Kideco Jaya Agung, *Jurnal Ilmu Teknik Sriwijaya*, 2(1) [in Indonesian].

Life cycle GHG emission considerations in overland conveyor design

T Hicks[1]

1. Manager of Decarbonisation Mining and Metals, Bechtel, Brisbane Qld 4006.
   Email: tjhicks@bechtel.com

ABSTRACT

Designers of mining facilities play a significant role in defining the overall mine greenhouse gas emissions performance. This demands an appreciation of all the greenhouse gas emissions sources, including Scope 3 emissions, which will form an increasing fraction of the emissions as we transition our generation sources to renewable energy.

Traditionally overland conveyors are designed to operate as fast as practical, and through this approach, achieve relative minimisation of: conveyor belt tensions; belt width; mechanical equipment masses; structural steel quantities; and concrete quantities. It is well understood that higher belt speeds reduce capital cost and improve project economics. Operating at higher speeds introduces operating costs through system energy losses and increased wear rates.

This paper assesses the life cycle greenhouse gas emissions for a typical iron ore overland conveyor to demonstrate how the design criteria and engineering decisions impact greenhouse gas emissions and project economics. An analysis of the decarbonisation potential and project economics using a range of operational parameters has been completed, developing a marginal abatement cost for each system configuration, creating a basis for integration of low emission overland conveyor designs as part of the broader facility decarbonisation strategy.

INTRODUCTION

The designers of mining facilities play a significant role in defining a mine's overall Greenhouse Gas (GHG) emissions performance. This demands greater awareness of all the GHG emissions sources, including Scope 3 emissions, which will make up an increasing fraction of emissions as power generation sources shift to renewable energy.

Traditionally overland conveyors are designed to operate as fast as practical, achieving benefits of reduced: tensions; conveyor belt width; mechanical equipment masses; structural steel; and concrete quantities. Higher belt speeds reduce capital cost and improve project economics. However, operating at higher speeds also introduces operating costs through increased energy losses and wear rates.

This paper presents the findings of the life cycle emissions from an overland conveyor under a range of design parameters to demonstrate how the design criteria and design decisions impact GHG emissions and project economics. For this assessment we developed a theoretical project with a single overland conveyor located in the Pilbara region of Western Australia, using inputs based on our typical project execution and operational strategies for a project in this region.

OPTION DEVELOPMENT

Eight conveyor configurations were developed over a broad range of belt speeds to allow evaluation of designs outside of the typical design norms. A relatively short overland conveyor of 1015 m was selected representing typical mine applications including transport from primary crushing to processing facilities as well as large in plant or stockyard conveyors.

Conveyor design

Eight conveyor designs were developed with common performance requirements of

- Design capacity: 7000 t/h.
- Length: 1015 m.
- Lift: 15 m.

- Material: Iron ore -230 mm:
  - Bulk density: 2000 kg/m^3.
  - Surcharge angle: 20 degrees.
  - Particle top size (P_{100}): 230 mm.
  - Abrasion Index (French): 0.3 g.
- Design basis: CEMA 7.
- Cross-sectional Area (CSA) utilisation: 80 per cent CEMA (unless otherwise noted).

The options with the widest belt (Options 1 and 2) and the narrowest option (Option 8) are in real terms impractical for this duty but have been included in the study to improve our understanding at the extremes. The eight conveyor options are:

- Option 1 2400 mm: 1.65 m/s, ST3150, 1 × 1100 kW.
- Option 2 2000 mm: 2.40 m/s, ST2500, 1 × 1100 kW.
- Option 3 1800 mm (100 per cent CSA): 2.39 m/s, ST3150, 1 × 1100 kW.
- Option 4 1800 mm (90 per cent CSA): 2.65 m/s, ST3150, 1 × 1100 kW.
- Option 5 1800 mm (80 per cent CSA): 2.99 m/s, ST2000, 1 × 1100 kW.
- Option 6 1600 mm (Base Case): 3.81 m/s, ST2000, 1 × 1250 kW.
- Option 7 1400 mm: 5.03 m/s, ST2000, 1 × 1320 kW.
- Option 8 1200 mm: 6.94 m/s, ST1600, 1 × 1320 kW.

1500 mm wide belt is a more typical standard used in the mining industry. 1400 mm and 1600 mm have been used in the analysis to provide some additional granularity between the 1200 mm and 1800 mm standards.

Option 6 was selected as the base (or reference) case for development of all the capital, operating and GHG emission indices. The design base for this study was a relatively short and high capacity overland conveyor, often designed to operate in the 4 to 5 m/s range. Option 7 also falls within the typical design envelope for a conveyor with this duty and could have equally been used as the base case.

The vertical profile selected for the study introduced a vertical curve limitation for Option 4 driven by belt lift. For this study, a ST3150 carcass was selected to eliminate the issue, resulting in increased system mass and motor power. The option could be further optimised through reprofiling the vertical curves. This would increase the embodied emissions as well as the civil and structural capital costs, with an expected benefit over the life of the asset. For this analysis all the options maintained a common conveyor profile.

The criteria selected for the study resulting in design outputs including:

- 20 per cent delta in power demand.
- 15 per cent delta in steel mass.
- 215 per cent delta in belt tensions.
- 44 per cent delta in concrete volumes.

Capital costs

Capital costs have been developed using input quantities from engineering based on the preliminary design of each of the options. Supply and install pricing utilised recent historical and benchmark data. A capital cost index was developed with the base case as unity. Capital cost indices are presented in Table 1 and Figure 1.

TABLE 1
Capital costs and embodied carbon.

Option	Capital cost index (relative to base case)	Embodied emissions (t CO_2e)	Embodied carbon index (relative to base case)
Option 1 2400 mm	1.12	2890	1.25
Option 2 2000 mm	1.05	2632	1.14
Option 3 1800 mm (100% CSA)	1.03	2525	1.09
Option 4 1800 mm (90% CSA)	1.04	2539	1.10
Option 5 1800 mm (80% CSA)	1.01	2564	1.11
Option 6 1600 mm (Base Case)	1.00 (Base)	2311	1.00
Option 7 1400 mm	0.98	2239	0.97
Option 8 1200 mm	0.95	2269	0.98

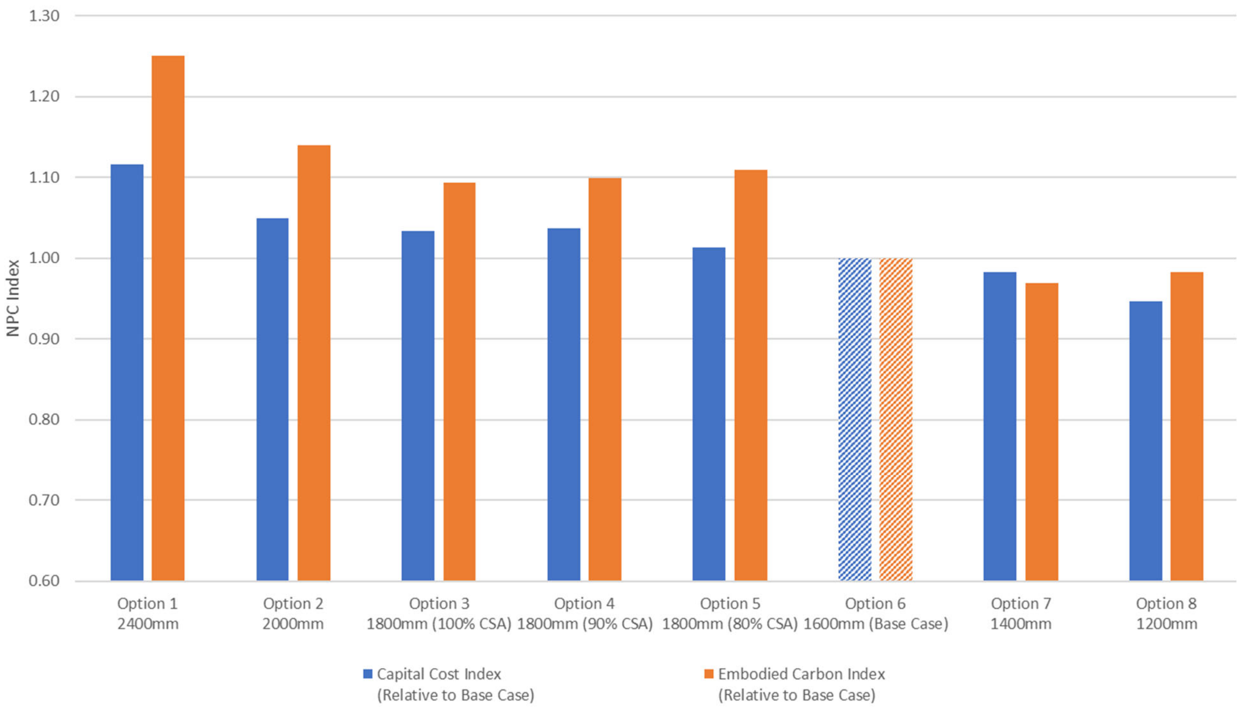


FIG 1 – Capital cost and embodied carbon index.

Embodied ghg emissions

To develop the embodied GHG emissions an assessment of the materials and work required to procure, transport, construct, and commission the facility was completed. The embodied emissions assessment was developed using an approach aligned with the GHG protocol, including estimates for scope 1, scope 2 and scope 3 emissions (Greenhouse Gas Protocol, 2013). Scope 3 emissions estimates included all the upstream categories required to execute the works, including:

- Purchased goods and services.
- Capital goods.
- Fuel and energy related activities not included in Scope 1 and Scope 2.
- Upstream transportation and distribution.
- Waste generated in operations.
- Business travel.
- Employee commuting.

Downstream scope 3 emissions were not included in this assessment as they are either not relevant, or in the case of operational use categories have been included in the life cycle assessment.

Embodied emissions for each of the options were calculated using the methods presented below. As with the capital costs, an embodied emission index was developed with the base case as unity. Embodied emissions and indices are presented in Table 1 and Figure 1.

Mobile combustion

Mobile combustion GHG emissions are calculated for all vehicle operations required to execute the works. A construction equipment schedule was generated for each option which estimated the vehicle class, vehicle type and engine class, and operating time. For each option the total mobile fleet fuel estimate was developed.

The mobile combustion GHG emissions estimate was calculated:

$$E_{MC} = \sum \mathrm{F}_v (EF_{CO2} + EF_{CH4} + EF_{NO2}) \quad (1)$$

Where:

$E_{MC} = Total\ GHG\ Emissions\ from\ Mobile\ Combustion\ (t\ CO_2e)$

$F_v = \mathrm{Total}\ fuel\ use\ by\ fuel\ type\ and\ vehicle\ (\mathrm{L})$

$EF_{CO2} = \mathrm{CO_2}\ Emission\ Factor\ (t\ CO_2e.L^{-1})$ (Assumes 100 per cent oxidation of carbon content in fuel)

$EF_{CH4} = \mathrm{CH_4}\ Emission\ Factor\ (t\ CO_2e.L^{-1})$

$EF_{N02} = \mathrm{NO_2}\ Emission\ Factor\ (t\ CO_2e.L^{-1})$ (NOx factors specific to motor/vehicle type where available).

Where the construction equipment was electrified, the demand energy use was calculated and included in the stationary combustion load list.

Stationary combustion

Stationary combustion GHG emissions are calculated for all non-mobile plant and equipment required to execute the works. Electrical loads were calculated for construction equipment, administration, and camp facilities to generate an electrical load list.

Hydrocarbon fuelled equipment emissions were calculated using equation [1] above where the total fuel use was estimated from historical productivity factors, equipment scheduling and equipment fuel efficiencies.

The stationary combustion GHG emissions estimate was calculated:

$$F_{gen} = E_{elec}.\frac{1}{HV_F.\mu_{gen}.\mu_{he}} \quad (2)$$

$$E_{SC} = \sum(\mathrm{F}_S + \mathrm{F}_{gen}).(EF_{CO2} + EF_{CH4} + EF_{NO2}) \quad (3)$$

Where:

$E_{SC} = Total\ GHG\ Emissions\ from\ Stationary\ Combustion\ (t\ CO_2e)$

$F_{gen} = Total\ generator\ fuel\ use\ (L)$

$F_S = Total\ stationary\ equipment\ fuel\ use\ (L)(excludes\ generators)$

$E_{elec} =$ Total electricity energy demand for the project (kWh)

$HV_f =$ Net Calorific Content of the fuel (LHV) (kWh/L)

$\mu_{he} =$ Thermal efficiency of the heat engine

$\mu_{gen} =$ Average system efficiency of the generator based on historical performance

Construction equipment is based on conventional diesel powered equipment with temporary power provided by diesel generators.

Purchased goods and services and capital goods

Bulk materials and equipment embodied emissions per ISO 14025 cradle to gate (module A1-A3) are calculated using cascading sources:

- Supplier Environmental Product Declarations (EPD).
- Embodied Carbon in Construction Calculator (EC3).
- Factored based on material masses and make up using Inventory of Carbon and Energy (ICE) database version 3.0.

$$E_{PG} = E_{CG} = \sum Q_G . EF_G \quad (4)$$

Where:

$E_{PC} = Total\ GHG\ Emissions\ from\ Purchased\ Goods\ and\ Services\ (t\ CO_2e)$

$E_{CG} = Total\ GHG\ Emissions\ from\ Capital\ Goods\ (t\ CO_2e)$

$EF_G =$ Gradle to gate emission factor for goods $(t\ CO_2e/uom)$

$Q_G =$ Quantity of goods (uom)

Note that the unit of measure for purchased goods and services as well as capital goods varies dependent on the type of good. For this assessment each good is categorised by a standard unit of measure by commodity code with corresponding supplier emission factor. Supplier data norms vary and must be converted to a common unit base.

Upstream transportation and distribution

Freight allowances as well as provision for supplier quality surveillance for equipment and bulks have been assumed to be supplied from locations which are typical for a Pilbara based project.

- Conveyor drives: Germany
- Conveyor belt: Perth, Australia
- Pulleys: Sydney, Australia
- Idlers: Perth, Australia
- Structural steel: Tianjin, China
- Electrical and instrumentation bulks and equipment: Perth, Australia
- Construction equipment mobilised from within the Pilbara region.

Freight to site includes a mix of road and sea transport. Conveyor components have been assumed to be containerised wherever possible.

Freight emissions have been calculated based on the total number of vehicle movements, transportation distance and vehicle fuel efficiencies.

$$E_F = \sum F_F(EF_{CO2} + EF_{CH4} + EF_{NO2}) \tag{5}$$

$$F_F = \sum D.FE.(Max\left(\frac{F_V}{Cap_V}, \frac{F_M}{Cap_M}\right)) \tag{6}$$

Where:

$E_F = Total\ GHG\ Emissions\ from\ Freight\ (t\ CO_2e)$

$F_F = Total\ freight\ fuel\ use\ (L)$

$D = Distance\ travelled\ for\ freight\ leg\ (km)$

$FE = Vehicle\ fuel\ efficiency\ based\ on\ loading\ condition\ (L/km)$

$Cap_V =$ Volumetric Capacity of the vehicle including load utilisation $(m^3/load)$

$Cap_M =$ Mass Capacity of the vehicle including load utilisation $(t/load)$

$F_V =$ Total volume of item to be transported (m^3)

$F_M =$ Total mass of item to be transported (t)

Waste generated in operations

Waste emissions from the construction phase are estimated using historical norms for each of the following categories:

- Packaging, grillage and cribbing for capital goods
- Construction consumables and distributables
- Waste associated with operation of the remote camp including liquid and solid wastes.

GHG emissions from waste are calculated using the 2006 IPCC methodology in Chapter 5: Waste (Pipatti and Vieira, 2006). Waste calculation methodology which has not been replicated here.

$$E_W = Total\ GHG\ Emissions\ from\ Waste\ (t\ CO_2e)$$

Business travel and employee commuting

The construction workforce is based on a fly-in fly-out crew with a Perth based point of origin. The construction schedule uses a 13 day rotation with a 10.5 hr per shift. Installation productivity and total project job hours are based on historical performance factors.

Travel emissions are calculated using the total vehicle travel distances, fuel efficiency standards and assumed travel distances.

$$E_{BT} = E_{EC} = \sum F_V(EF_{CO2} + EF_{CH4} + EF_{NO2}) \tag{7}$$

$$F_V = \sum D.FE.\left(TM.V_{Cap}.V_{Util}\right) \tag{8}$$

Where:

$D = Distance\ travelled\ for\ leg\ (km)$

$FE = Vehicle\ fuel\ efficiency\ (L/km)$

$E_{BT} = Total\ GHG\ Emissions\ from\ Business\ Travel\ (t\ CO_2e)$

$E_{EC} = Total\ GHG\ Emissions\ from\ Employee\ Commuting\ (t\ CO_2e)$

$TM = Travel\ movements\ per\ travel\ type$

$V_{Cap} = Vehicle\ total\ seat\ capacity\ (\frac{seats}{vehicle})$

$V_{Util} = Vehicle\ Seat\ utilisation\ (\%)$

Fuel estimates were calculated for private vehicle usage, air transport, taxi, and third party operated busses.

Fugitive emissions

Fugitive emissions are calculated using the total gas leakage allowances from plant and equipment using refrigeration cycles. Leakage allowances are calculated using gas charge, gas type and leakage allowance per the Australian National Greenhouse Accounts Factors (Department of Climate Change, Energy, the Environment and Water, 2023).

$$E_{Fu} = \sum \mathrm{L}_{Fu}(EF_x) \tag{9}$$

Where:

$E_{Fu} = Total\ GHG\ Emissions\ from\ Fugitive\ Leakage\ (t\ CO_2e)$

$L_{Fu} = Total\ mass\ of\ leakage\ (t)$

$EF_x = \text{Emission Factor for CFCs, PFCs, etc}\ (t\ CO_2e)$

Fuel and energy related emissions

Fuel and energy related emissions from upstream refining and transport are calculated using the total fuel usage estimates and fuel specific emission factors for the region.

$$E_{FE} = \sum \mathrm{F}_V(EF_{CO2e}) \tag{10}$$

The total embodied emissions for each of the options is calculated using the sum of each of the emissions calculated above as shown in Figure 2a. The calculation methodology also assigns each emission to a commodity type within the facility as shown in Figure 2b.

$$E_{Em} = \mathrm{E}_{MC} + \mathrm{E}_{SC} + \mathrm{E}_{PG} + \mathrm{E}_{CG} + \mathrm{E}_F + \mathrm{E}_W + \mathrm{E}_{BT} + \mathrm{E}_{EC} + \mathrm{E}_{Fu} + \mathrm{E}_{FE} \tag{11}$$

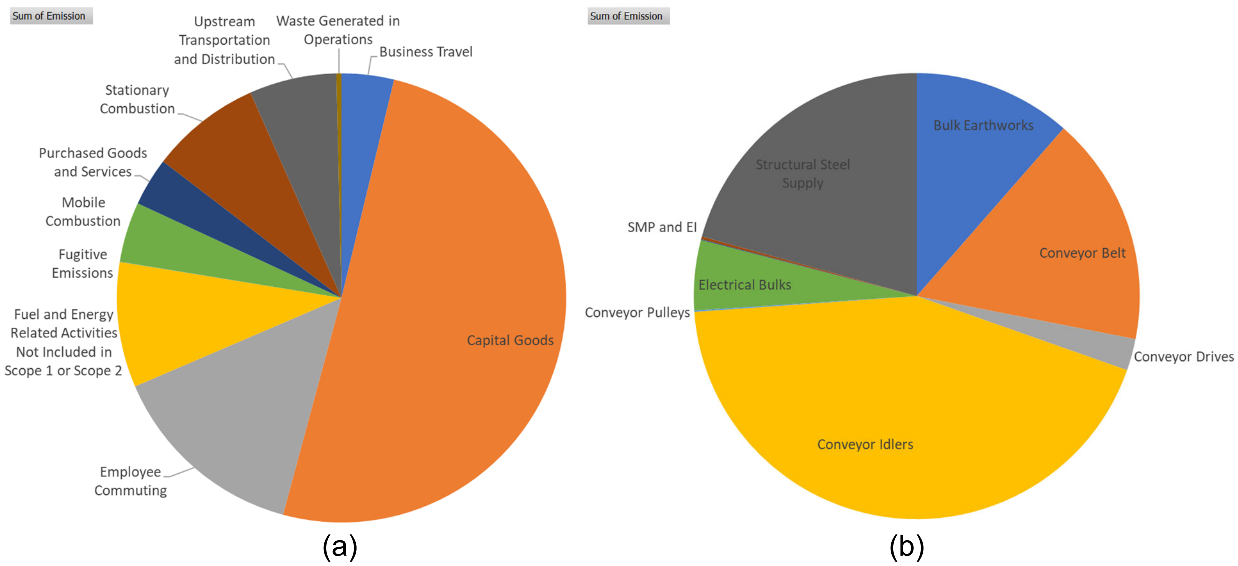


FIG 2 – Embodied GHG Emissions by: (a) GHG protocol category, (b) supply package.

The current 'as fast as practical' design paradigm holds for capital costs and embodied emissions. However, it may result in a sub-optimal solution over the operational life of the system.

LIFE CYCLE ASSESSMENT

The life cycle assessment considers the operational emissions in addition to the embodied. For mining operations, the operational emissions will exceed the embodied emissions by a large factor. Operational emissions must consider direct (Scope 1) and indirect (Scope 2) as well as the value chain emissions (Scope 3). Scope 3 emissions are particularly important to evaluate in the design phase, where the asset owner and designer have the greatest influence over the Scope 3 emissions profile through selection of technology and duty cycles. The ability to influence Scope 3 emissions after scope lock can be limited and for purchased goods and services are largely reliant on suppliers and the procurement process.

For the life cycle assessment for this study, we ran our model using a 20-year operational life, considered three different power supply options, and evaluated two carbon pricing models. These criteria provide a range of scenarios typical of a mining investment in Western Australia.

Emission sources

Life cycle emissions calculations for the project are based on the Scope 1, 2 and 3 emissions during the operational phase of the asset in addition to the embodied emissions noted above and include:

- power consumption for all drives, including equipment idle time
- embodied emissions in purchased goods and services
- transportation of goods, services, and waste to and from site
- operations and maintenance plant and equipment, assumed to be diesel powered
- business travel
- employee and contractor commuting
- waste
- overhead/general and administration, such as camp operation, water supply and wastewater treatment.

For this assessment, the end of life and benefits beyond the boundary (ie reuse/recycling) have not been included.

Emissions from the operating phase of the project are calculated using the same methods as defined in Equations 1 to 11, with the inputs adjusted to match the operating phase of the project.

Power assumptions

The three power supply options used for the life cycle assessment were:

1. Combined Cycle Gas Turbine, natural gas fuel with a thermal efficiency of 58 per cent.
2. Behind the metre (BTM) unfirmed solar. Annual energy supply to the facility is assumed as 19 per cent renewable with the balance of power supplied by CCGT.
3. Green Power Purchase Agreement (PPA). The PPA has been assumed as a firmed power supply arrangement with no Scope 2 GHG emissions.

The generator options were selected to provide representation of simplified generation options that a miner may be considering. The CCGT base case was selected for this study as it aligned with the legacy generation assets in the Pilbara region of WA; The green PPA option is typical of many mining operations which have either transitioned or are investigating renewable energy sources; finally the unfirmed solar option was selected to assess the benefit of a relatively low capital cost behind the metre solution. More remote operations may be considering diesel generation options which would result in a large increase in Scope 1 and Scope 3 emissions from the lower thermal efficiencies, higher relative carbon content and higher upstream fuel and energy related emissions.

The total GHG emissions and relative emissions intensity for each of the options are summarised in Table 2 and Figure 3.

TABLE 2
Life cycle emissions.

Option	Life cycle emissions (kt CO_2e)			Life cycle emissions index (index)		
	CCGT	BTM	PPA	CCGT	BTM	PPA
Option 1 2400 mm	50.9	38.1	4.9	0.84	0.63	0.08
Option 2 2000 mm	52.8	39.6	5.5	0.87	0.65	0.09
Option 3 1800 mm (100% CSA)	54.1	40.5	5.6	0.89	0.67	0.09
Option 4 1800 mm (90% CSA)	55.4	41.4	5.5	0.91	0.68	0.09
Option 5 1800 mm (80% CSA)	56.0	42.4	7.2	0.92	0.70	0.12
Option 6 1600 mm (Base Case)	60.8	45.6	6.5	1.00 (Base)	0.75	0.11
Option 7 1400 mm	69.0	52.7	10.7	1.13	0.87	0.18
Option 8 1200 mm	69.6	53.5	12.1	1.14	0.88	0.20

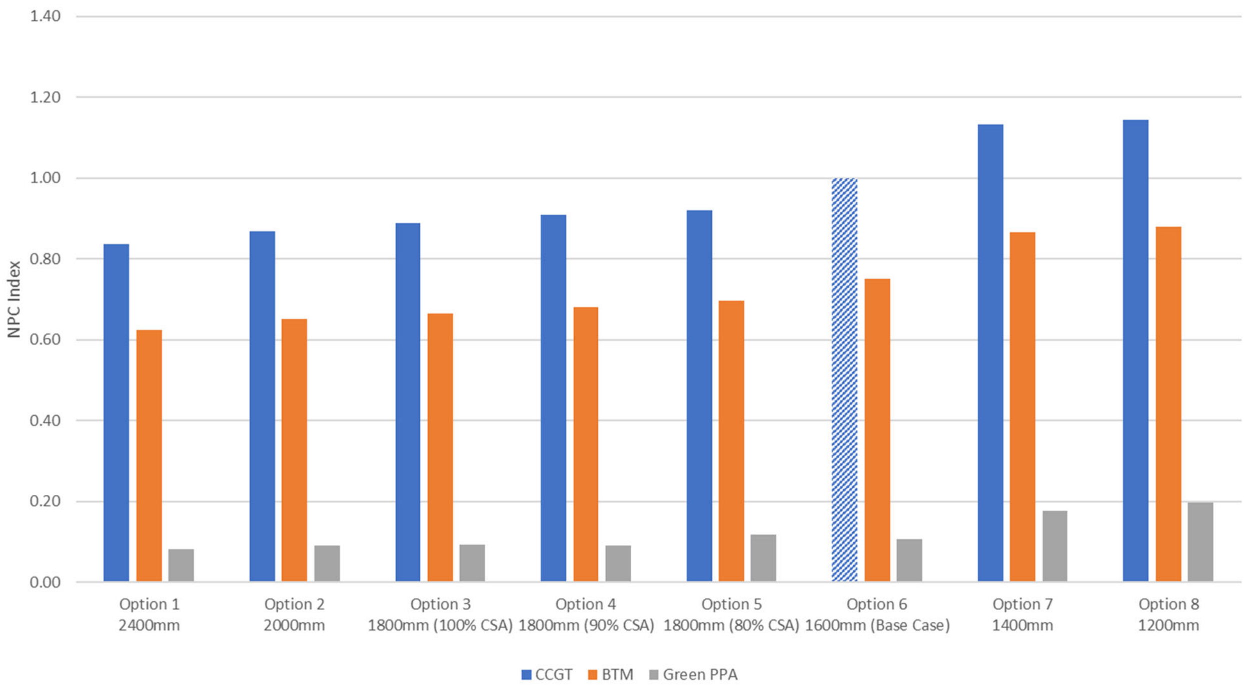


FIG 3 – Life cycle emissions index.

Naturally, the biggest reductions are made through securing a low emissions power source, resulting in an approximate reduction of 88 per cent for each conveyor design. Whilst the power source is the largest influence on GHG performance, optimisation of the facility life cycle emissions intensity can be achieved through consideration and selection of the design parameters. This influence is most apparent where power is provided through a green PPA where the lowest emission option (Option 1) has a 60 per cent lower emissions footprint than the highest emission option (Option 8).

For the CCGT options the typical distribution of GHG emissions by scope for this assessment was:

- Scope 1: 0.5 per cent.
- Scope 2: 87.6 per cent.
- Scope 3: 11.9 per cent.

The ratio of embodied to life cycle emissions for the options where power supply was by CCGT ranged from 3.3 per cent for Option 8 to 5.7 per cent for Option 1 with an average of 4.3 per cent.

Scope 3 emissions from each of the options varied, with higher belt speeds resulting in greater the proportions of Scope 3 emissions increasing in line with the belt speed. The total Scope 3 emissions for Options 1 through 4 were approximately 10 per cent, increasing up to 17 per cent for Option 8. The increase in Scope 3 emissions is driven by the reduced mechanical equipment life and associated increase in site labour.

The Scope 1 and Scope 3 emissions by source are summarised in Table 3 for the base case, with the sensitivities shown for Option 3 and Option 8. The most significant contributor to the increase was the conveyor belt, and the indirect emissions associated with transport, installation, and waste. For the base case, the conveyor belt and conveyor belt site support activities represented 64.2 per cent of the total life cycle emissions. The second largest emission source was general operations. In addition to the large contribution from the conveyor belt and operations sources the sensitivity to design change was also large for these sources, driven by rates of wear and reliability.

TABLE 3

Scope 1 and 3 life cycle emissions breakdown.

Source	Scope 1 and 3 emissions breakdown	Scope 1 and 3 emissions sensitivity (Δ from base case)	
	Option 6 1600 mm (Base Case)	Option 3 1800 mm (100% CSA)	Option 8 1200 mm
Conveyor belt	64.2%	-33%	+128%
Conveyor drives	2.8%	-11%	-48%
Idlers	7.1%	+52%	+70%
Misc equipment	0.3%	-27%	+13%
Pulleys	1.4%	+18%	-47%
Operations	24.1%	-39%	+201%
	100%	-27%	+133%

Understanding the drivers for overall emissions sources allows the design and owner teams to select a design basis which meets the strategic direction. This is increasingly important as the decarbonisation strategy focus is expanding to include Scope 3 emission sources.

Life cycle costs

Life cycle costs for each of the options were estimated using operating expense estimates with allowances for:

- power
- maintenance parts

- maintenance labour
- operations labour
- overhead/general and administration.

Power supply costs for the analysis are summarised as:

- CCGT $37.03 US$/MWh.
- BTM $31.45 US$/MWh inclusive of $7.68 for operation of the renewables facility.
- PPA $45.50 US$/MWh.

The total renewable energy supply for the BTM options has been assumed to have a 19 per cent capacity factor with the balance of power supplied by CCGT.

Reference supply costs have been informed using publicly available information (Carland, 2022; Lazard, 2023; Lovegrove *et al*, 2018).

All costs are discounted with a discount rate of 8 per cent and an inflation allowance of 2.5 per cent.

For consistency, the carbon price allowance of US$100/t CO_2e has been applied to all scopes, whilst the mine operator will not be responsible for indirect carbon emission costs it has been assumed that future carbon costs from upstream supply chain pricing will be passed on to the consumer. Ultimately the impacts of carbon pricing on supply packages will be dependent on many factors outside the scope of this investigation. The selected approach provides a simplified conservative view on the risk of carbon pricing on project economics.

A Net Present Cost (NPC) estimate for each of the options was completed using the Option 6 with CCGT power supply as the base case. The results of the NPC analysis are summarised in Table 4 and Figure 4.

TABLE 4

Net present cost index.

Option	US$0 carbon price (index)			US$100 carbon price (index)		
	CCGT	BTM	PPA	CCGT	BTM	PPA
Option 1 2400 mm	0.95	1.01	0.98	1.19	1.21	1.00
Option 2 2000 mm	0.95	1.01	0.98	1.19	1.21	1.00
Option 3 1800 mm (100% CSA)	0.95	1.00	0.97	1.20	1.21	1.00
Option 4 1800 mm (90% CSA)	0.95	1.01	0.98	1.21	1.22	1.01
Option 5 1800 mm (80% CSA)	1.01	1.07	1.04	1.26	1.29	1.08
Option 6 1600 mm (Base Case)	1.00 (Base)	1.07	1.03	1.28	1.30	1.07
Option 7 1400 mm	1.21	1.27	1.24	1.51	1.54	1.30
Option 8 1200 mm	1.39	1.46	1.43	1.69	1.74	1.49

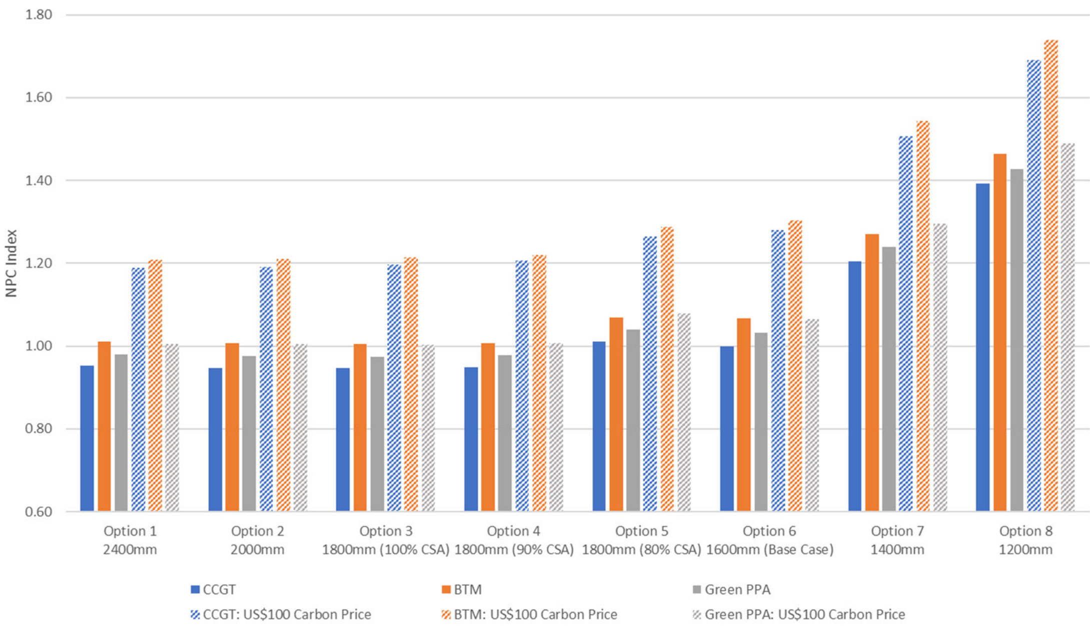


FIG 4 – Net present cost index.

The NPC analysis shows a general trend towards improved project economics with lower conveyor speeds for all power supply and carbon pricing models. For all cases there is little to no economic benefit and marginal GHG emission reductions for any of the options where a wider than 1800 mm belt is selected. Further to this, capital intensity must also be considered as this is often a key metric for project feasibility. With these considerations in mind, a design which balances GHG emissions, capital costs and asset value is Option 4, notably this option has a belt speed of 2.65 m/s, significantly lower than the current industry norm.

Marginal abatement costs

An alternative approach to assessment of the design basis is through development of Marginal Abatement Cost (MAC) for each option. The primary goal of this approach is to present the cost efficacy of plant design strategies to reduce GHG emissions intensity for comparison with other initiatives the project or broader business is considering.

The MAC can be used in support of a higher capital cost option, where the demonstrated GHG reduction MAC is favourable to the other strategies. As with the above analysis we used Option 6 as the base case and developed a MAC for each strategy.

The MAC for each option has been calculated using:

$$MAC = \frac{\Delta NPC}{AE} \tag{12}$$

$$\Delta NPC = \sum_{t=0}^{20} \frac{(R_{to} - R_{tb})}{(1+i)^t} \tag{13}$$

$$AE = \sum E_o - E_b \tag{14}$$

Where:

$AE = \ Abated\ Emissions\ (t\ CO_2e)$

$i = \ discount\ rate\ (\%)$

$MAC = Marginal\ Abatement\ Cost\ (\$.(t\ CO_2e)^{-1})$

$NPC = Net\ Present\ Cost\ (\$)$

$R_{to} = \ Option\ cash\ outflow\ in\ year\ t\ (\$)$

$R_{tb} = \ Base\ case\ cash\ outflow\ in\ year\ t\ (Option\ 6)(\$)$

$t = \ time\ period\ (year)$

The MAC for all the options demonstrated negative relative costs for all belt speeds lower than the base case ranging from -86 to -165 US$/t CO_2e abated where the power was supplied by CCGT, and -16 to -18 US$/t CO_2e where power was provided through a green PPA.

Noting that the greatest opportunity to reduce operational emissions is to secure firmed green energy, supplementing this with targeted designs which minimise emissions can bring both economic and environmental performance benefits to the project which are cost competitive with other decarbonisation strategies currently being assessed.

UNCERTAINTY

Estimation of greenhouse gas emissions over a project life cycle has a level of uncertainty and ambiguity associated with undefined allowances and changes to future supply chain, fuel mix, energy efficiency and process technology advances.

GHG emission estimate accuracy for the embodied phase can be estimated with a reasonably high level of accuracy with similar approaches to capital cost estimating, where suppliers, contractors, and execution methodology are selected and defined. The approach mirrors those as defined in the AACE cost estimate classification system (AACE, 2005). Notwithstanding the approach, meeting AACE Class 1 or Class 2 level estimates may be challenging where reliant on supply chain information.

The uncertainty assessment for the operational phase, and hence life cycle emissions is far more challenging, where the emissions magnitude and unknown future impacts are more difficult to define. The approach to life cycle emissions as presented here is intended to support development of low emission facility designs based on best available information, rather than development of accurate forward-looking emissions forecasts.

OPPORTUNITIES

Additional opportunities to further improve the GHG performance of the conveyor system were identified for further consideration.

Supplier selection

Selection of the suppliers based on environmental performance and energy efficiency is a key input into the optimisation process. As noted in the above analysis, energy efficiency governs, and the designer must work closely with the suppliers to select equipment which maximises efficiency. Specific examples here have not been completed; however, it is expected that the life cycle emissions and marginal abatement costs for high efficiency solutions will bring value to the project. In addition to energy efficiency, the project should consider the upstream emissions and decarbonisation strategies of the suppliers as part of the technical and commercial bid evaluation process.

Speed based control using volumetric and mass flow rate control

One of the primary drivers for the overall performance of the system was energy consumption and wear. One strategy to reduce these is through intelligent speed control using volumetric and weightometer based control. Through this strategy the conveyor speed can be adjusted to maximise the volumetric capacity of the belt and minimise speed. This would be particularly beneficial for many mining operations where equipment is designed for peak rates and conservative material properties (density, surcharge angle).

The primary issue this approach introduces is management of material flow-through the transfer chutes where variable discharge trajectories will impact chute operation. Careful study and optimisation of the operational boundaries, namely belt speed with the design of the chute can be used to achieve benefit here with little impact on capital cost.

Chute design

Impact and abrasion wear at the chute to belt interface is a critical consideration on belt life. Chutes functional designs typically require minimum velocities to ensure reliable flow as well as often being designed to approximate conveyor horizontal velocity. Where materials are relatively free flowing there is an opportunity to reduce material velocity in the chute improving the life of the chute and wear liners, this approach needs to consider the downstream impacts on belt wear life where reduced chute velocities influence the impact energy and loading acceleration zone. Through careful consideration a design compromise which meets the chute, conveyor and overall system life and reliability, and hence environmental performance can be made.

Loading point and skirt design

Conveyor belt wear is often accelerated on the carry side where the skirts interface with the belt. Belt replacement is often necessary due to insufficient cord coverage in this region only, with a significant wear life remaining in the rest of the top cover. Wear in this region is a function of the belt speed, chute and skirt designs and can be improved through minimisation of the material acceleration zone, skirt contact pressures and material lateral pressure in the skirted zone.

CONCLUSIONS

The paper developed a design basis for assessing whether the current design approach to maximising conveyor belt speed is aligned with the transition to a net zero emissions future. To complete this assessment a range of conveyor designs and operating parameters were developed to calculate the embodied and life cycle emissions, as well as assess the economic impacts. From this study the current strategy meets the short-term requirements of minimisation of capital cost, and in doing so minimisation of embodied emissions, however when life cycle emissions are considered an alternative paradigm brings value.

Reducing the design speed for the reference case tested herein provided both economic and environmental benefit to the project, with a relatively minor penalty to capital intensity. Further to the benefits it was demonstrated that the marginal abatement costs were attractive and could offer benefit over other strategies to reduce GHG emissions.

The approach recommended in this paper is to undertake a detailed assessment of the emissions performance of the facilities being designed and include consideration of all emissions sources including Scope 3. Value chain emissions will become increasingly important in decarbonisation of the mining industry as the early wins in energy supply are being won. Scope 3 emissions are by nature out of direct control of the miner, influence can be made through purchasing, however the greatest wins can be made in the design phase.

From the above it is clear that the business as usual faster-is-better design paradigm needs to be challenged given the need to achieve decarbonisation across the whole value chain. Using a structured approach during the design phase with consideration of the life cycle emissions can result in facility designs that reduce operational emissions and improve the overall project economics.

REFERENCES

AACE, 2005. International Recommended Practice No. 18R-97 Cost Estimate Classification System – as applied in engineering, procurement and construction for the process industries, February 2005.

Carland, D, 2022. Future Australian Electricity Generation Costs – A Review of CSIRO's GenCost 2021–22 Report, September 2022.

Department of Climate Change, Energy, the Environment and Water, 2023. National Greenhouse Accounts Factors, July 2023. Australian National Greenhouse Accounts Factors, July 2023.

Greenhouse Gas Protocol, 2013. Technical Guidance for Calculating Scope 3 Emissions, Version 1.0:2013.

Lazard, 2023. Lazard's Levelized cost of energy Analysis – Version 16, April 2023.

Lovegrove, K, James, G, Leitch, D, Milczarek, A, Ngo, A, Rutovitz, J, Watt, M and Wyder, J, 2018. Comparison of Dispatchable Renewable Electricity Options: Technologies for an orderly transition, Australian Renewable Energy Agency, 2018.

Pipatti, R and Vieira, S, 2006. IPCC Guidelines for National Gas Inventories, Volume 5 Waste, 2006, Intergovernmental Panel on Climate Change.

Toward the green mining – utilisation of tailings on gold recovery in thiosulfate system

S Jeon[1], A Buronov[2], I Park[3], C B Tabelin[4], L Godirilwe[5], K Haga[6] and A Shibayama[7]

1. Faculty of International Resources Science, Akita University, Akita, Japan.
   Email: jeon@gipc.akita-u.ac.jp
2. Graduate School of International Resources Science, Akita University, Akita, Japan.
   Email: azizburon1@gmail.com
3. Faculty of Engineering, Division of Sustainable Resource Engineering, Hokkaido University, Hokkaido, Japan. Email: i-park@eng.hokudai.ac.jp
4. Faculty of Engineering and Technology, Mindanao State University – Iligan Institute of Technology, Philippines. Email: carlito.tabelin@g.msuiit.edu.ph
5. Faculty of International Resources Science, Akita University, Akita, Japan.
   Email: llgodirilwe@gipc.akita-u.ac.jp
6. Faculty of International Resources Science, Akita University, Akita, Japan.
   Email: khaga@gipc.akita-u.ac.jp
7. Faculty of International Resources Science, Akita University, Akita, Japan.
   Email: sibayama@gipc.akita-u.ac.jp

ABSTRACT

Open pit/underground mining and mineral processing can generate large amounts of waste that contains sulfide-type minerals such as pyrite (FeS_2), and it can produce acid mine drainage (AMD) when exposed to oxygen and water. This highly acidic wastewater contains heavy metals and this is one of the most serious environmental issues after mining operations taking several decades to completely remediate with high costs. For green mining, the present study focused on the development of a recovery technique for gold from an eco-friendly solvent, thiosulfate, by utilising mine wastes, tailings. First, gold recovery experiments in ammonium thiosulfate system were carried out using model samples representatively present in tailings (ie SiO_2, Al_2O_3, FeS_2, Fe_2O_3, and Fe_3O_4). The results showed that gold recoveries were negligible when using Al_2O_3, SiO_2, Fe_2O_3, and Fe_3O_4 while pyrite shows a recovery efficiency three-fold as high as the maximum recovery efficiency when using others. Subsequently, the study also addressed the identification of the recovery mechanisms and post-recover process. The results indicate that tailings can be sufficiently utilised for gold recovery in the hydrometallurgy process and a further sustainable process can be established.

INTRODUCTION

In July 2023, the UN sounded a warning by highlighting a new era of climate change, ie global boiling that the need to reduce greenhouse gas emissions is more urgent than ever before and climate action is not an optional but a must. This circumstance specifically targets the electric power/heat generation and transport sectors to replace fossil fuels with renewable green energy technologies. Produce green energy technologies, however, are much more metals intensive than conventional fossil fuel technologies, thus, stable supplies of those critical metals are significantly critical in the next 50 years for the clean energy transition's success. Among the critical metals, gold, in particular, is in the spotlight since it is not only used in the aforementioned green technologies but also essential for technologies such as catalysts to convert CO_2 into fuels or a catalyst in photovoltaic (PV) cells to enhance the solar energy capture.

In gold-hydrometallurgy, conventionally cyanide or halides (eg aqua regia) solvents have been employed in the first extraction stage due to their high efficiencies. Although effective, cyanide is seriously toxic in the ecological systems causing solid/atmosphere pollution and death including humans even with a very low concentration of exposure in a very short time (eg >100 ppm/30 min) while halides are strongly corrosive and unselective for precious metal extraction. With the recent emphasis on the importance of the environment, the phenomenon has been a further critical issue in the resources field. Moreover, a radical change in resources is also having a great impact. Increasingly, high-concentration gold ores have been depleted while low-grade refractory ores have been continuously enhanced. Those low-grade refractory ores sometimes contain high carbonaceous matter, which is able to give a low extraction efficiency in the conventional cyanide because of the preg-robbing phenomenon (ie adsorption of the gold-cyanide complex to carbonaceous matters in ore), hence engineers/researchers have been speeding up research on the investigation of alternative eco-friendly solvents to address aforementioned environmental and resource issues. Among the alternatives, thiosulfate has been highlighted because of its non-toxicity, non-corrosiveness, and high selectivity for precious metals (Jeon *et al*, 2018). Although this eco-friendly solvent is perfectly suitable for the current trends, its application to the industrial plant is still limited to date primarily for two big issues, which are:

1. 'Economic feasibility is low (ie high reagent consumption) due to the thiosulfate decomposition reaction.
2. Acceptable recovery technique is elusive to date' (Jeon *et al*, 2022).

To briefly explain the mineral processing, the ore is first pulverised, valuables are concentrated and separated from the gangue (ie non-valuables), only concentrates then go to the metallurgical process while gangue minerals are disposed into the tailings dam. In the case of tailings in gold mines, quartz (SiO_2), aluminium oxide (Al_2O_3), pyrite (FeS_2), magnetite (Fe_3O_4) and/or hematite (Fe_2O_3) in general. When the tailings are exposed to atmospheric conditions and meet oxygen and water, especially pyrite, they generate acidic leachate containing highly toxic elements called acid mine drainage (AMD). Japan has more than 5000 closed or abandoned mines, which can continuously generate AMD, and JX Nippon Mining and Metals Corporation operates 12 treatment facilities in their closed mines. Australia has more than 52 000 and the USA has more than 555 000 closed or abandoned mines, costly >140 000 000 yen per day for AMD treatment. Researchers in the resources and environmental field are conducting various studies to solve the issues such as further developing AMD treatment technologies (eg passive/active treatment) as well as tailing surface treatment (eg microencapsulation of the tailings to suppress the AMD) (Park *et al*, 2021) or using it as a resource (eg recovery of critical metals from tailings) (Chen *et al*, 2022) as for the advanced research. The present study goes a step further to apply problematic tailings to develop a novel recovery stage in the most highlighting eco-friendly solvent thiosulfate system in hydrometallurgy while solving thiosulfate decomposition that negatively affects the economic aspects ie upgrading of gold concentration and separation in a concurrent process.

MATERIALS AND METHODS

Materials

For the gold recovery experiments, pyrite (Huanzala mine, Huánuco, Peru), hematite, magnetite, aluminium oxide, and quartz (-75 μm, 99.99 per cent, Wako Pure Chemical Industries, Ltd., Japan) were used.

Methods

Ammonium thiosulfate solutions with pH around 9.5–10 containing 1 M $Na_2S_2O_3$, 0.5 M NH_3, 0.25 M $(NH_4)_2SO_4$, and 10 mM $CuSO_4$ (Wako Pure Chemical Industries, Ltd., Japan) with 100 mg/L of gold ions were used in the Au recovery experiments. The solution containing 100 mg/L of gold(I) ions (ie gold(I)-thiosulfate solution) was prepared by dissolving 0.01 g of gold powder (99.999 per cent, Wako Pure Chemical Industries, Ltd., Japan) in 100 mL of ammonium thiosulfate solution using 300 mL Erlenmeyer flasks shaken in a water bath shaker at 25°C for 24 hr with constant shaking amplitude and frequency of 40 mm and 120 min^{-1}, respectively.

For the gold recovery experiments, 0.1 g of samples (ie quartz (SiO_2), pyrite (FeS_2), hematite (Fe_2O_3), and magnetite (Fe_3O_4)) with 10 mL of gold(I)-thiosulfate solution in a 50 mL Erlenmeyer flask at 25°C (shaking amplitude of 40 mm and frequency of 120 min^{-1}) under the atmospheric conditions. After experiments, the leachate and residue were separated by filtration using 0.2 μm syringe-driven membrane filters (LMS Co., Ltd., Japan). The residues were washed thoroughly with deionised water (18 MΩ cm, Milli-Q® Integral Water Purification System, Merck Millipore, USA), dried in a vacuum oven at 40°C, and analysed by SEM-EDS (InTouchScope™, JSM-IT200, JEOL Ltd., Japan) and XPS (JPS-9200, JEOL Ltd., Japan) while the filtrates were analysed by ICP-AES

(ICPE-9820, Shimadzu Corporation, Japan; margin of error = ±2 per cent). For accuracy and replicability of results, experiments were done in triplicates, and the final recovery was averages of the experiments.

RESULTS AND DISCUSSION

Recovery of gold(I) from ammonium thiosulfate solution was carried out using model samples representatively present in tailings (ie SiO_2, Al_2O_3, FeS_2, Fe_2O_3, and Fe_3O_4). Figure 1 shows the gold recovery results, and results showed that gold recoveries were negligible when using Al_2O_3, SiO_2, Fe_2O_3, and Fe_3O_4 while pyrite shows a recovery efficiency three-folds as high as the maximum recovery efficiency when using hematite with following conditions: 1 M $Na_2S_2O_3$, 0.5 M NH_3, 0.25 M $(NH_4)_2SO_4$, 10 mM $CuSO_4$, 10 ppm of gold ions, 25°C, 1 g/10 mL of solid-to-liquid ratio, pH 9.5, 120 rev/min, 24 hr. The pyrite showed the highest recovery; hence, subsequent gold recovery experiments were focused on this system.

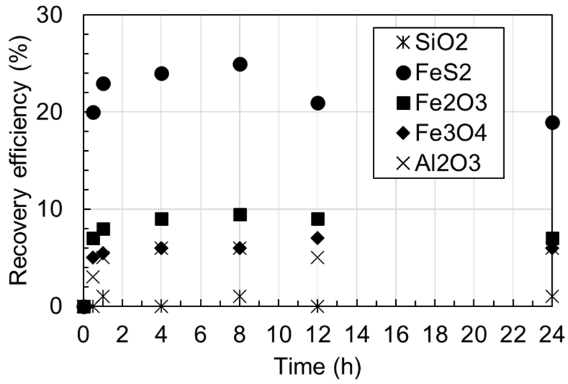


FIG 1 – Recovery of gold ions from ammonium thiosulfate solution with mineral model samples present in tailings (ie SiO_2, FeS_2, Fe_2O_3 and Fe_3O_4).

The effects of various parameters (ie initial gold concentration, shaking speed, pH, temperature, and solid-to-liquid ratio) were also investigated, and over 85 per cent of gold could be recovered under the conditions: 0.1M $Na_2S_2O_3$, 0.5 M NH_3, 0.25 M $(NH_4)_2SO_4$, 10 mM $CuSO_4$, 100 ppm of gold ions, 25°C, 0.1 g/10 mL of solid-to-liquid ratio, pH 11, 140 rev/min, 4 hr.

The residue was analysed by SEM-EDS and XPS, and the results showed that on the surface of pyrite after gold recovery experiments in the thiosulfate system, the signal of S was enhanced in comparison to before gold recovery experiments. This can be elucidated by the thiosulfate decomposition reactions. In the thiosulfate system, thiosulfate can be naturally decomposed by oxygen (Equations 1, 2, and 3), the reaction however can be further enhanced when sulfide-type ore, ie pyrite, is present in the system (Mhandu *et al*, 2023):

$$3S_2O_3^{2-} + 6H_2O \rightarrow 2SO_4^{2-} + 4S^0 + 2OH^- \quad (1)$$

$$3S_2O_3^{2-} + 6OH^- \rightarrow 4SO_3^{2-} + 2S_2^- + 3H_2O \quad (2)$$

$$S_2O_3^{2-} \rightarrow SO_3^{2-} + S^0 \quad (3)$$

The surface property of S layers, which is a precipitation of the sulfur species onto the pyrite generated from thiosulfate decomposition reactions shows highly hydrophobic (Walker, Walters and Richardson, 1986). For the post-recovery process, when bubbles are injected during the recovery process like flotation, bubbles can be attached to the S layers onto the pyrite surface having gold particles, then eventually be recovered as a froth while others like quartz can remain as tailings, that can expect a concurrent stage of recovery/upgrading and separation process.

CONCLUSIONS

Recovery of gold(I) from ammonium thiosulfate solution using model samples representatively present in tailings (ie SiO_2, Al_2O_3, FeS_2, Fe_2O_3, and Fe_3O_4) was carried out. The results showed that the pyrite obtained the maximum recoveries among the minerals present in tailings. The effects of various parameters on gold recovery using pyrite were carried out and results showed that over

85 per cent of gold could be recovered under the conditions: 0.1 M $Na_2S_2O_3$, 0.5 M NH_3, 0.25 M $(NH_4)_2SO_4$, 10 mM $CuSO_4$, 100 ppm of gold ions, 25°C, 0.1 g/10 mL of solid-to-liquid ratio, pH 11, 140 rev/min, 1 hr. The pyrite residue after gold recovery was analysed by SEM-EDS and XPS and results showed that the signal of S was enhanced in comparison to before gold recovery experiments due to the thiosulfate decomposition reactions. The generated S layers show the highly hydrophobicity and this can be utilised for the post-recovery process by injecting bubbles, then eventually be recovered as a froth while others like quartz can remain as tailings, that can expect a concurrent stage of recovery/upgrading and separation process.

The present study aims to develop a method for recovering gold in an eco-friendly system, thiosulfate, utilising tailings (ie by-products; non-valuables), which can cause significant environmental issues and incur high treatment costs in mining systems. The results achieved high recovery efficiency with availability, confirming the feasibility of establishing a fully sustainable gold-hydrometallurgy scheme.

ACKNOWLEDGEMENTS

The authors wish to thank the Japan Society for the Promotion of Science (JSPS) grant-in-aid for Early career researchers (grant number: 24K17540).

REFERENCES

Chen, W, Yin, S, Zhou, G, Li, Z and Song, Q, 2022. Copper recovery from tailings through bioleaching and further application of bioleached tailings residue: Comprehensive utilization of tailings, *Journal of Cleaner Production,* 332:130129.

Jeon, S, Bright, S, Park, I, Tabelin, C B, Ito, M and Hiroyoshi, N, 2022. A simple and efficient recovery technique for gold ions from ammonium thiosulfate medium by galvanic interactions of zero-valent aluminum and activated carbon: A parametric and mechanistic study of cementation, *Hydrometallurgy*. 208:105815.

Jeon, S, Ito, T, Tabelin, C B, Pongsumrankul, R, Kitajima, N, Park, I and Hiroyoshi, N, 2018. Gold recovery from shredder light fraction of E-waste recycling plant by flotation-ammonium thiosulfate leaching, *Waste Management*, 77:195–202.

Mhandu, T J, Park, I, Jeon, S, Hamatsu, S, Elakneswaran, Y, Ito, M and Hiroyoshi, N, 2023. A Pretreatment of Refractory Gold Ores Containing Sulfide Minerals to Improve Gold Leaching by Ammonium Thiosulfate: A Model Experiment Using Gold Powder and Arsenic-Bearing Sulfide Minerals, *Metals*, 13(8):1357.

Park, I, Higuchi, K, Tabelin, C B, Jeon, S, Ito, M and Hiroyoshi, N, 2021. Suppression of arsenopyrite oxidation by microencapsulation using ferric-catecholate complexes and phosphate, *Chemosphere*, 269:129413.

Walker, G W, Walters, C P and Richardson, P E, 1986. Hydrophobic effects of sulfur and xanthate on metal and mineral surfaces, *International Journal of Mineral Processing*, 18(1–2):119–137.

Getting it right from the beginning – ESG in mineral exploration

L H G McClean[1]

1. Managing Director, Forelight Advisory, Sydney NSW 2000.
Email: lucy.mcclean@forelight.com.au

ABSTRACT

Environmental, social and governance (ESG) factors have always been important to the minerals industry and is now considered one of our most important opportunities (and risks). Getting it right from the beginning is critical for the minerals industry, and that starts with mineral exploration.

Exploration, or the process of investigation of an economic mineral deposit, is generally low impact and short-term. Exploration operations vary in size and scale and often shift priority, focus and location relatively quickly. Australia is a highly regulated jurisdiction with different regulatory systems and requirements in every state and territory. Most mineral exploration is undertaken by junior exploration companies or 'explorers'. Exploration companies are lean operations with limited staffing and resources, traditionally with no income apart from funds raised or work through partnerships. Funds are tight and administrative investment is minimised so that investment into activity on the ground is maximised. All these variables mean that understanding and implementation of ESG frameworks for an exploration company can be challenging.

ESG is a fast-moving sector with currently multiple frameworks and reporting standards. Interest from community and government stakeholders as well as investors and off-take partners has been growing, with mandatory reporting soon to be implemented. The upcoming changes to the JORC Code will ensure that ESG considerations will be a key component of all public reporting. Resources have been developed to support explorers implement, manage and report on ESG considerations.

Due to their scale, agility and direct importance of land access and social licence, many explorers are not the 'cowboys' (or 'cowpersons') of the industry, but industry leaders in ESG. Strong interest and leadership have led to innovative practices and strongly embedded vertical frameworks that directly contribute to social licence to operate.

INTRODUCTION

'ESG' (environment, social and governance) may be a new acronym but is not a new concept for the minerals industry. All minerals industry companies 'do ESG'. ESG is the price to play, and the price to stay.

ESG considerations for the minerals industry refers to their impact (planned, real and perceived). Generally, ESG today also refers to the framework used by an organisation including their practises and performance, on a range of sustainability and ethical issues. Over the years, the key considerations of what we now call ESG have also been known as 'sustainability', 'triple bottom line', or 'corporate social responsibility'.

Operators and miners in the minerals industry generally have a well-developed understanding and governance for ESG. ESG factors can be a 'showstopper' for mining operators. Generally, ESG is considered just behind safety in importance for operators, from worksites to board rooms.

For mineral exploration, ESG is just as, if not more, important. Depending on jurisdictional requirements, unless ESG factors are well managed, a company will generally not be able to gain access to land for exploration. Mineral exploration companies are usually the first exposure local regions have to the minerals industry, and so it is essential to 'get it right from the beginning'.

EXPLORATION FINDS THE MINES OF TOMORROW

Mineral exploration is the scientific process working towards discovery of an economic mineral deposit. Most mineral exploration programs are low impact and short-term. Mineral exploration is highly speculative, with the probability of exploration targets developed to mine assessed as 1 in 24 (for brownfield exploration) to as low as 1 in 1000 to 3333 for greenfield exploration (Kreuzer and

Etheridge, 2010). Exploration operations can vary in size and scale, with project priority and so location reviewed regularly. Australia is considered a highly regulated country for the minerals industry, with different legislative frameworks and requirements in every state and territory.

Exploration companies (also known as junior companies or explorers) are responsible for most successful exploration worldwide. These companies are generally lean operations with limited staffing and resources, traditionally with no income apart from funds raised privately or through the share market. Activity is undertaken using these funds or through equity sharing in partnerships and joint ventures. Funds are usually tight and administrative investment is minimised so that investment into exploration activity on the ground is maximised. Exploration companies and their work in mineral exploration is a significant part of the mining sector, with exploration employing over 20 000 people in Australia, around half the number employed in the coal industry (ABS, 2023).

Mineral explorers have been described as the 'cowboys' (or 'cowpersons') of the mining industry. These companies attract the entrepreneurs of the industry, with strong pioneering spirit and a drive for success. In truth, these companies are agile and more successful than the major companies. Schodde (2023a) states that over the last decade, 63 per cent of all mineral deposits globally and 73 per cent of the deposits in Australia were found by junior companies. These companies accounted for 45 per cent of the exploration spend and capture 61 per cent of the value for the industry, '*demonstrating that they are doing much more of the heavy lifting than the major companies'*.

With the average cost of discovery of a mineral deposit now US$218 million (having tripled in less than ten years) and time taken to develop a mine is near 20 years (Schodde, 2023b), dedication, determination and resilience are needed in this sector of the industry.

ESG IS IMPORTANT FOR ALL SECTORS OF THE MINERALS INDUSTRY

The interest from regulators, local communities and other stakeholders and investors in ESG risks has been increasing for the minerals industry (Maybee, Lilford and Hitch, 2023) and now very much front of mind. For the third year in a row, ESG has been rated as the biggest risk and opportunity for the minerals industry in the 2024 EY annual survey of mining and metals (EY, 2024). The top five ESG factors that were nominated as facing the most scrutiny (from 17 options) were local community impact; tailings and waste management; water stewardship; attaining net-zero emissions; diversity, equity and inclusion.

Most companies understand that ESG is essential for social licence and survival. A review of over 300 of the world's largest undeveloped copper orebodies revealed that, even for this most sought-after element, the ESG issues mean that even with high copper pricing, the environmental and social impact of development of 96 per cent would be 'unacceptable' (Valenta *et al*, 2019).

Tragically, there have been very public examples of the cost to the company, environment and local communities when companies have 'got it wrong'. These issues then cause tremors across the wider industry – one Australian mineral exploration company working in a Scandinavian country was asked by the local people how they could be trusted following the destruction of rock shelters at Juukan Gorge by Rio Tinto, another by local people in regional NSW (pers comm).

ESG FACTORS IN MINERAL EXPLORATION

There are a wide range of ESG issues that would be considered important at the exploration stage of the mining cycle. ESG considerations that relate to mineral exploration (AMEC, 2023a; JORC, 2024) include:

- **Environmental** – Flora, fauna, biodiversity, water, air, noise, waste, pollution, rehabilitation, emissions, energy, climate change.
- **Social** – Landholder/community/stakeholder rights and engagement, First Nations/Indigenous rights and engagement, cultural heritage, safety, labour rights, talent attraction and retention, security, well-being, gender, diversity and inclusion, modern slavery and human rights, crisis response and corporate legacy.

- **Governance –** Corporate governance (purpose/values, strategy and plans), tenure and approvals, compliance, commercial agreements (JV, landholder, First Nations), corporate reporting (to government, regulators, ASX, JV partners and shareholders), investor/government/regulatory requirements, management systems (environmental, safety, quality, social), sustainability rating, procurement, due diligence, data integrity and protection, market disclosure, conflict of interest and confidentiality.

The ESG considerations will vary significantly depending on the location of the exploration programs, as well as scope and maturity of the exploration programs. Importantly, ESG priority and implementation also varies and does not always align with company size or projects – a small company may have a highly developed ESG framework, while a larger company may have a less mature or embedded framework.

THE MAZE OF ESG FRAMEWORKS AND RESOURCES

ESG is a fast-moving sector with currently multiple published frameworks and reporting standards. There is a plethora of ESG frameworks and reporting standards, considered by many as an 'alphabet soup'. Some of the best-known frameworks include the United Nations Sustainable Development Goals (SDGs), Global Reporting Initiative (GRI), World Economic Forum (WEF) and International Sustainability Standards Board (ISSB). These standards vary, with different levels of detail, parameters and reporting, although there are many similarities between many frameworks. However, there is not yet a universally or even generally accepted ESG standard

As well as general frameworks and standards, there are also industry specific standards. For the minerals industry, most focus on operational aspects of the industry, not mineral exploration, as detailed in Figure 1.

General	Minerals Industry-Specific	Exploration-Specific
UN Global Compact	International Council for Mining and Metals (ICMM) Principles	IRMA – developing exploration-specific standards
UN Sustainable Development Goals (SDGs)	Towards Sustainable Mining (TSM)	JORC – proposal to extend the code to ESG modifying factors
Global Reporting Initiative (GRI)	Initiative for Responsible Mining Assurance (IRMA)	
International Sustainability Standards Board (ISSB)	Responsible Mining Foundation (RMF)	
Task Force on Climate-Related Financial Disclosures (TCFD)	*The Copper Mark*	
Sustainability Accounting Standards Board (SASB)	Global Reporting Initiative (GRI) 14: Mining Sector Standard	
Taskforce on Nature-Related Financial Disclosures (TNFD)		
World Economic Forum (WEF)		
Stakeholder Capitalism Metrics (WEF-SCM)		
International Organization for Standardization (ISO 14000, 2600 etc)		

FIG 1 – ESG standards and governance frameworks related to mining and exploration (ICAA, 2024).

The number and scope of the standards for the mining industry has been growing, including the recent release of *GRI 14: Mining Sector Standard* (GRI, 2024). However, the Copper Mark, Mining Association of Canada, International Council on Mining and Metals and the World Gold Council announced that they were working to consolidate their voluntary mining standards into a single mining standard and multiple stakeholder oversight system, responding to feedback from investors, industry and the communities that a single global standard would be clearer, more transparent and practical so encourage wider industry implementation (World Gold Council, 2023).

More broadly, as the ESG sector matures, a single standard will probably dominate, gain acceptance by regulators, investors, governments and communities so lead to mandatory or expected implementation.

ESG NO LONGER A 'NICE TO HAVE'

Reporting on ESG factors is now imminent for mineral exploration in Australia, with the government also committed to climate reporting.

Of specific relevance to mineral exploration, the recently released draft changes to the JORC Code (Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves) include ESG as a '*key area of change*' (JORC, 2024).

The JORC Code is widely respected and utilised by the minerals industry in Australia (and beyond) as well as regulatory organisations including the ASX (Australian Stock Exchange) as a guide for company preparation of public reports for investors and advisors on mineral deposits. This includes annual and quarterly corporate reports, media releases, website information and public presentations (JORC, 2024).

The amendments related to ESG in the draft changes to the JORC Code in the include:

- Clauses related to ESG including disclosure of material considerations.
- Addition of reporting criteria (Table 1, section 5.5).
- Addition of a guidance matrix.
- Allowance for specialist assistance to support the Competent Person.

JORC states that the intention of the changes is to increase awareness of ESG and the importance of ESG disclosure throughout the exploration-mining cycle as well as increase disclosure requirements appropriate to the stage of the project (JORC, 2024).

Depending on the detail of the final version of the updated JORC Code, effectively this means that ESG will be a mandatory component of public reporting. This will be a significant step change for the minerals industry.

Additionally, the Australian Government is committed to introducing mandatory climate-related financial disclosures to improve transparency for both government and communities (Australian Government, 2024). This aligns with other countries internationally including UK and EU that have mandated climate reporting.

In Australia, the climate related financial disclosures will be mandated through amendments to the Corporation Act 2001 and related regulatory framework with detailed standards to be maintained by the Australian Accounting Standards Board (AASB) and the Australian Auditing and Assurance Standards Board (AUASB). These disclosures are currently planned to apply only to large companies (with at least two of the criteria of minimum revenue of \$50 million; assets of \$25 million; 100 employees) so will not impact most exploration companies. However, reporting includes scope 3 emissions (ie emissions from up and down the supply chain and emissions associated with financing and investment activities), so may include reporting on some exploration activities, for example, when part of joint venture arrangement or an operating asset.

Compliance will be a key component of mandatory reporting and ASIC has already issued infringement notices for alleged false or misleading sustainability statements in public disclosures (known as 'greenwashing'), with the first landmark case resulting in an \$11.3 million penalty (ASIC, 2024). Compliance action may be extended to false or misleading carbon emissions statements, termed as 'carbonwashing' (In and Schumacher, 2021).

ESG RESOURCES FOR EXPLORERS

Understanding ESG and the implications for mineral exploration can be challenging for exploration companies that generally have lean resourcing.

Industry associations are supporting their members by producing resources that support understanding and implementation. These include the industry first *AMEC Guide for Mineral Explorers on ESG* (AMEC, 2023a) and QEC *Voluntary ESG Framework* (QEC, 2023). These guides provide clear information on ESG and applications for mineral exploration with accompanying information for practical implementation and case studies.

Resources have also been developed to support mineral explorers with different aspects of ESG. Community engagement is a particularly important matter and there are many references produced by governments that are jurisdictionally specific as well as the usually more comprehensive guides produced by industry associations. These include the *AMEC Land Access Toolkit for Mineral Exploration in NSW* (AMEC, 2023b) and *AMEC Land Access Toolkit for Mineral Exploration in Victoria* (AMEC, 2022), *Land Access Guide* (Minerals Council of Australia and Victorian Farmers Federation, 2020) and *First Engagement: A Field Guide for Explorers* (PDAC, 2015).

EXPLORERS INNOVATE TO IMPLEMENT ESG FRAMEWORKS

Exploration companies may have lean resourcing, but the leaders of these companies are often directly involved in leading exploration programs (and often significant shareholders), so have a direct understanding of the importance of investing in ESG to maximise the success of exploration projects. Today, companies are implementing ESG frameworks and publishing ESG or sustainability reports, over and above mandatory government compliance reporting. Companies see value in reporting to provide transparency and align with investor and stakeholder expectation and so improve social licence.

For most companies, implementing an ESG framework is no more than formalising or organising what is already undertaken as part of regular operations. This includes understanding what is important (known as materiality), understanding risk and opportunities, compiling data aligned to agreed metrics, reporting and reviewing to improve the process. Working within an ESG framework can be aligned with the well-known 'Plan-Do-Check-Act' process as shown in Figure 2.

FIG 2 – The process of ESG implementation for mineral exploration (AMEC, 2023a).

The industry resources to support ESG provide clear step-by-step support for implementation including tables and factsheets. Some companies utilise an online platform such as Socialsuite or Digbee that align with varying published standards and may offer certification.

Implementation of an ESG framework should align with the company objectives and maturity. It can be as simple as reviewing company strategies, policies and procedures, compiling agreed metrics and then including an ESG section in the corporate annual report. Importantly, the ESG system for any company should be designed to be dynamic and grow as appropriate, something that is especially important for exploration companies that generally have agile operations.

Importantly, the implementation of an ESG framework needs to be a shared activity across the organisation – all representatives of a company, from the company Chair and Managing Director to the field assistant and contractors have an important role to support implementation and management of ESG. If not, the ESG framework can become the equivalent of a dusty procedure manual that sits on an old shelf – the ESG framework should become part of a company's DNA and guide operations.

ESG ACTIVITIES IN PRACTICE FOR MINERAL EXPLORATION

Exploration companies, especially operating in sensitive jurisdictions, are motivated to implement great practice in ESG to establish and maintain social licence. Many companies align with the philosophy that '*the cost of getting it wrong outweighs the cost of getting it right*'.

Australia has strong ESG requirements as part of compliance in most jurisdictions. NSW Government notes that an independent review of the NSW ESG credentials for the minerals industry shows the state's regulatory processes has 97 per cent compliance with the International Council on Mining and Metals (ICMM) performance expectations and 100 per cent compliance with Initiative for Responsible Mining Assurance (IRMA) performance expectations and so promotes '*invest in NSW for safe and sustainable mining and exploration'* (NSW Government, 2023).

Companies often exceed compliance requirements, even in highly regulated jurisdictions. Motivation includes the need to better align with community expectations and support social licence as well as the ethical objective of simply doing the right thing.

Examples of good practice in ESG activities mineral exploration include:

- **Environment** – Gifting a tree seedling for every drill hole (over and above all other compensation and full rehabilitation); fixing a gate or fence; installing a permanent water bore for a landholder after drilling discovered water (particularly welcome if found during drought conditions).
- **Social** – Supporting community initiatives such as a sports team or community activity such as bushfire relief; providing community information on the company website with information of interest such as factsheets and newsletters; standing up a community advisory or consultative group to provide regular opportunity for the company and community to meet and work together or work through issues; holding 'town hall' meetings or open days on-site; working to become an active member of the local community and 'good corporate citizen'.
- **Governance** – Regularly updating strategies to align with exploration maturity and progress; developing an app for use by all team members on their smartphones to record all contact with landholders.

As noted, community engagement is generally agreed as one of the most important ESG factors and this is especially true for mineral exploration that often occurs on land owned by another party. Getting it right from the beginning is simply essential to achieving and maintaining land access and so critical to the success of exploration.

RECOMMENDATIONS FOR IMPLEMENTATION OF ESG FRAMEWORKS

Just as for all systems in a company, the implementation of an ESG framework or amending ESG governance requires consideration, planning, resourcing and management. This is especially important for mineral exploration companies with lean resources.

Recommendations to support successful implementation include:

- Reflect on the purpose and values of the company and alignment with ESG considerations.
- Develop a framework that is aligned to the company objectives, maturity and resourcing.
- Ensure the framework is sustainable.
- Ensure the framework is embedded in all part of the company operations and is dynamic.
- Assess reporting options including content, frequency and method of reporting.
- Develop clear and consistent metrics.
- Develop and maintain great recordkeeping.
- Report honestly and regularly on ESG factors.
- Ensure that all public statements reflect the ESG priorities.
- Ensure that all public statements are justifiable.
- Review framework to ensure continued alignment with the company stage and focus.

Importantly, it is never too early to implement an ESG framework. Early implementation can save retrofitting a framework to a mature organisation and ESG frameworks can grow and change to align with a company.

CONCLUSION

Due to their scale, agility and direct importance of land access and social licence, many explorers are not the 'cowboys' (or 'cowpersons') of the industry, but industry leaders in ESG. Strong interest and leadership have led to many companies implementing innovative practices in ESG and strongly embedded vertical frameworks that directly contribute to social licence to operate.

The upcoming changes to the JORC Code will necessitate a step change in ESG reporting for mineral exploration. There has never been a more important time for the minerals industry to 'get it right from the beginning'.

ACKNOWLEDGEMENTS

The author thanks the many exploration companies that she has worked with and special thanks to RN (Sam) Lees who first employed her in this industry that she has been so honoured to work in and serve.

For transparency, the author initiated, led and drafted the AMEC Guide for Mineral Explorers on ESG (AMEC, 2023a), AMEC Land Access Toolkit for Mineral Exploration in NSW (AMEC, 2023b) and AMEC Land Access Toolkit for Mineral Exploration in Victoria (AMEC, 2022).

REFERENCES

Association of Mining and Exploration Companies (AMEC), 2022. AMEC Victorian Land Access Toolkit or Mineral Exploration, February 2022. Available from: <https://amec.org.au/amec-victorian-land-access-toolkit-for-mineral-exploration/> [Accessed: 4 July 2024].

Association of Mining and Exploration Companies (AMEC), 2023a. AMEC Guide for Mineral Explorers on ESG (Environment, Social, Governance), August 2023. Available from: <https://amec.org.au/wp-content/uploads/2023/12/NEW-ESG-Guide.pdf> [Accessed: 4 July 2024].

Association of Mining and Exploration Companies (AMEC), 2023b. AMEC NSW Land Access Toolkit or Mineral Exploration, August 2023. Available from: <https://amec.org.au/amec-nsw-land-access-toolkit-for-mineral-exploration/> [Accessed: 4 July 2024].

Australian Bureau of Statistics (ABS), 2023. Australian Industry Data. Available from: <https://www.abs.gov.au/statistics/industry/industry-overview/australian-industry/latest-release> [Accessed: 5 July 2024].

Australian Government, 2024. Policy Position Statement: Mandatory climate-related financial disclosures. Available from: <https://treasury.gov.au/sites/default/files/2024-01/c2024-466491-policy-state.pdf> [Accessed: 5 July 2024].

Australian Securities and Investment Commission (ASIC), 2024. ASIC’s first greenwashing case results in landmark $11.3 million penalty for Mercer. Available from: <https://asic.gov.au/about-asic/news-centre/find-a-media-release/2024-releases/24-173mr-asic-s-first-greenwashing-case-results-in-landmark-11-3-million-penalty-for-mercer/> [Accessed: 2 August 2024].

Ernst and Young (EY), 2024. Top 10 business risks and opportunities for mining and metals in 2024. Available from: <https://www.ey.com/en_au/mining-metals/risks-opportunities> [Accessed: 20 July 2024].

Global Reporting Initiative (GRI), 2024. GRI 14: Mining Sector 2024. Available from: <https://www.globalreporting.org/standards/standards-development/sector-standard-for-mining/> [Accessed: 15 July 2024].

In, S Y and Schumacher, K, 2021. Carbonwashing: A new type of carbon data-related ESG greenwashing. http://dx.doi.org/10.2139/ssrn.3901278> [Accessed: 5 July 2024].

International Copper Association, Australia (ICAA), 2024. Roadmap to Zero: Discovery Report. Available from: <https://copper.com.au/about/projects/roadmap-to-zero/> [Accessed: 1 August 2024].

JORC, 2024. Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC Code) Exposure Draft (and accompanying documents). Available from: <https://survey.alchemer.eu/s3/90736819/draftjorccodesurvey> [Accessed: 2 August 2024].

Kreuzer, O P and Etheridge, M A, 2010. Risk and Uncertainty in Mineral Exploration: Implications for valuing mineral exploration properties, *Australian Institute of Geoscientists News*, 100:20–28.

Maybee, B, Lilford, E and Hitch, M, 2023. Environmental, social and governance (ESG) risk, uncertainty and the mining life cycle, *The Extractive Industries and Society*, 14:101244. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S2214790X23000357> [Accessed: 5 July 2024].

Minerals Council of Australia Victorian Division and the Victorian Farmers Federation, 2020. Land Access Guide, Available from: <https://minerals.org.au/wp-content/uploads/2023/01/Introduction-to-Victorias-Minerals-Resources-Act-1990_July-2020.pdf> [Accessed: 5 July 2024].

NSW Government, 2023. Environmental, Social and Governance (ESG), NSW Government, Mining, Exploration and Geoscience. Available from: <https://meg.resourcesregulator.nsw.gov.au/sites/default/files/2023-11/environmental-social-governance-brochure.pdf> [Accessed: 5 July 2024].

Prospectors and Developers Association of Canada (PDAC), 2015. First Engagement: A Field Guide for Explorers, Available from: <https://www.pdac.ca/docs/default-source/priorities/responsible-exploration/programs---e3-plus---community-engagement-guide/pdac-first-engagement--a-field-guide-for-explorers.pdf?sfvrsn=e757a898_2> [Accessed: 5 July 2024].

Queensland Exploration Council (QEC), 2023. ESG Toolbox for Explorers. Available from: <https://esg.qe-connect.com.au/> [Accessed: 5 July 2024].

Schodde, R, 2023a. Outlook for the Australian Junior Sector, Presentation at Mines and Money, 2023. Available from: <https://minexconsulting.com/outlook-for-the-australian-junior-sector/> [Accessed: 5 July 2024].

Schodde, R, 2023b. Exploration: Australia vs The World, Presentation at IMARC, 2023. Available from: <https://minexconsulting.com/exploration-australia-vs-the-world/> [Accessed: 5 July 2024].

Valenta, R K, Demp, D, Owen, J R, Corder, G D and Lebre, E, 2019. Rethinking complex orebodies: Consequences for the future world supply of copper, *Journal of Cleaner Production,* 220:816–26. Available from: <https://www.sciencedirect.com/science/article/pii/S0959652619305359?via%3Dihub> [Accessed: 4 July 2024].

World Gold Council, 2023. Collaboration underway to develop consolidated standard for responsible mining. Available from: <https://www.gold.org/news-and-events/press-releases/collaboration-underway-develop-consolidated-standard-responsible> [Accessed: 4 July 2024].

Coalmine methane emission estimates – an evolving understanding

S Raval[1]

1. Associate Professor, School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney NSW 2052. Email: simit@unsw.edu.au

INTRODUCTION

The estimation of greenhouse gas emissions from coalmines is increasingly becoming a priority for both operators and regulators. At the same time, involved scientific challenges in the methane measurements is generating significant interest from global research community. Various technology providers are also actively engaged in improving their sensors and platforms to address the measurement challenges and capitalise the market opportunities. This presentation highlights rapidly evolving multifaceted landscape of coalmine greenhouse gas emissions. It covers the advances in sensors for the detections, including ground-based, airborne, and satellite-based systems as well as models for the emission estimations, including attempts to reduce the involved uncertainties.

METHANE SENSING SYSTEMS

The field of methane detection technology has undergone significant advancements in recent years. This progress is characterised by the development of portable sensors, fixed Unmanned Aerial Vehicles (UAVs), aircraft sensors, and satellite-based monitoring systems (Figure 1).

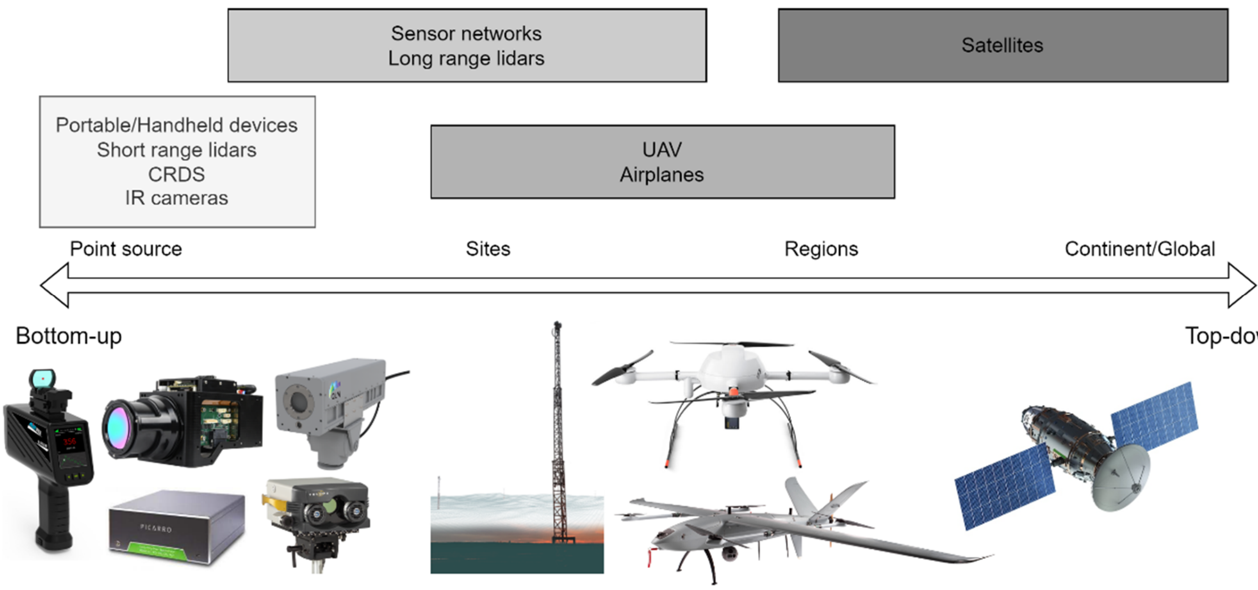


FIG 1 – The sensors and platforms for methane emission detection.

Ground-based systems

In the early days, sensors were bulky and stationary, with limited capabilities. However, the latter half of the 20th century brought significant improvements, introducing more sensitive and accurate laser-based and optical sensors. The trend towards miniaturisation in the late 20th and early 21st centuries led to the development of portable methane detectors, broadening their application to environmental monitoring and research. The introduction of infrared (IR) cameras in the early 2000s revolutionised methane detection by enabling real-time visualisation of gas leaks (Brandt *et al*, 2014; Fox *et al*, 2019).

A significant breakthrough came in 2010 with the introduction of the Picarro device. This point sampling system could detect and quantify methane with high accuracy and parts-per-billion-level sensitivity, within a measurement range of up to 100 parts per million (ppm). Further advancements in 2015 and 2017, the introduction of the GreenLite sensor and the Long Path sensor, respectively.

These laser-based systems featured a rotating transmitter and a receiver, enabling them to cover extensive areas of up to 25 km^2 (Dobler *et al*, 2013). The year 2017 also witnessed the development of the HiFlow portable sampler. Equipped with a catalytic oxidation sensor and a thermal conductivity sensor, it was the world's only commercially available portable device capable of accurately detecting and quantifying gas leakages directly from smaller components (Hendrick *et al*, 2016).

The IR camera industry also evolved, offering simpler structures and lower maintenance costs compared to active systems. However, these cameras required a significant temperature difference between the methane gas and its background to function effectively (Wang *et al*, 2023). The Kuva sensor, an IR camera, sought to overcome these limitations through advanced process algorithms, including machine learning, developed in partnership with Microsoft. FLIR Gx320-24, introduced with a detector maintained at absolute zero temperatures to significantly enhance performance. However, this technology came at a cost, being more than five times the price of standard detectors. The recent trend towards integrating various technologies was exemplified by the QLM quantum lidar which successfully completing testing in 2021. This system stood out for its enhanced versatility and accuracy across diverse environmental conditions (Wang *et al*, 2020).

Ground-based systems will continue to evolve, as evidenced by the Advanced Research Projects Agency-Energy (ARPA-E) MONITOR (Methane Observation Networks with Innovative Technology to Obtain Reductions) in the US, funding 12 research projects aimed at developing high-quality methane detection networks, with a focus on reducing costs while maintaining high measurement accuracy.

Airborne systems

The journey of aerial methane detection has evolved remarkably beginning with the use of manned aircraft to gather data for environmental monitoring. As the environmental impact of methane emissions gained greater attention, the focus shifted towards developing methane-specific sensors. These are the customised versions of ground-based sensors. A major breakthrough in this field came with the advent of Unmanned Aerial Vehicles (UAVs), which offered a more flexible, cost-effective, and safer alternative for methane surveillance.

PERGAM, a US company with a near-monopoly in producing sensors for UAVs, offers both thermal imaging and LiDAR-based payloads. These payloads, adaptable for handheld surveys, offer increased flexibility and value. In 2021, DJI, a leading drone manufacturer, partnered with PERGAM to integrate the FALCON sensor into their M600 and M210 drones, yielding impressive results. Additionally, DJI launched its U10 drone, a standalone methane detection unit. In 2023, DJI unveiled the Purway CH4 Laser Methane Leak Detector Model II, capable of detecting methane leaks up to 300 m away. That same year, Chevron collaborated with Bridger Photonics to deploy airplanes with advanced sensors for methane leak detection in pipelines and other infrastructure (Golston *et al*, 2018; Shah *et al*, 2020).

Over time, the technology of these sensors has seen substantial advancements, improving in sensitivity to detect lower methane levels and in spatial resolution, thus allowing for the pinpointing of specific emission sources.

Satellite-based systems

The European Space Agency (ESA) launched GOCE (Gravity Field and Steady-State Ocean Circulation Explorer), marking an early step in Earth observation technology, setting the stage for the development of more specialised environmental monitoring satellites. This was followed by the 2014 launch of the Greenhouse Gases Observing Satellite (GOSAT) and NASA's Orbiting Carbon Observatory-2 (OCO-2) in 2016. A major breakthrough came in 2017 with Sentinel-5 Precursor satellite, equipped with the TROPOspheric Monitoring Instrument (TROPOMI), significantly enhancing methane emission monitoring with its ability to detect a wide range of air pollutants. The private sector also made notable contributions; GHGSat launched its first satellite, Claire, in 2019 and GHGSat-C1 (Iris) in 2020, both designed for high-resolution monitoring of greenhouse gases (Jacob *et al*, 2016).

Since its installation on the International Space Station in July 2022, NASA's EMIT mission has demonstrated remarkable effectiveness in identifying methane 'super-emitters', successfully pinpointing over 50 such sources. EMIT's major advantage lies in its combination of wide coverage and high resolution, enabling it to map methane emissions accurately at the facility level. Moreover, the data collected by EMIT are publicly accessible, allowing scientists and organisations to develop their own identification and monitoring algorithms (Sherwin *et al*, 2023).

Recently, 4 March 2024, launched MethaneSAT is a significant project aimed at measuring and tracking global methane emissions, particularly from oil and gas operations. Its high precision design enables it to detect even small, localised methane sources. Additionally, the delayed MERLIN mission, a collaborative effort between France and Germany set for 2025, will focus on precise atmospheric methane measurements. Upcoming satellites like COOL and updated version of GHGSat are expected to offer even greater results.

MODELLING

Most instruments can only give out methane concentration values of either a point or a column averages. These datapoints map the spatial distribution of methane but do not directly offer the total volume of the methane present. To transform these discrete measurements to an understanding of the total methane flux or flow rates, it is essential to use robust modelling methods.

The Law of Mass Balance, one of the oldest methods for estimating methane volumes, is still extensively used in methane emission modelling. The equation has been modified over a period of time to adapt to various applications. For instance, over the last decade, researchers have been continuously developing algorithms for UAV and airborne-based quantification methods, incorporating the mass balance concept with various assumptions and modifications (Lamb *et al*, 1995).

The Gaussian Diffusion model is widely used to quantify methane emissions from continuous point sources, and it relies on diffusion coefficients. In its calculations, the model typically uses average values of these parameters, a practice that introduces uncertainty into the results (Sherwin *et al*, 2024). To improve accuracy, researchers have recently been investigating integration of this model with more comprehensive land surface models such as ORCHIDEE-PEAT. This integration aims to better determine meteorological parameters and thus enhance the precision of methane emission estimations (Yacovitch *et al*, 2015; Safitri, Gao and Mannan, 2011).

The United States Environmental Protection Agency (EPA) has developed Method 21, a protocol for detecting leaks of volatile organic compounds using specialised instruments. Following this, the EPA introduced OTM33a, a top-down approach to quantify methane emissions that is considered more user-friendly than previous methods. Still there is a great uncertainty about OTM33a estimations (Heltzel *et al*, 2020).

The latest advancement in this area is the use of model inversion methods. These rely on atmospheric diffusion models that calculate methane emission rates from measured concentrations, integrating information about source distribution, geographical conditions, and other relevant data (Li *et al*, 2019). The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model, developed by the US Air Resources Laboratory, represents a significant advancement in atmospheric diffusion modelling. Weather Research and Forecasting (WRF) models have also proven to be extremely useful. In 2020, researchers used WRF models to study the behaviour of methane in an open pit mine in Canada. They validated their results against aircraft observations, achieving a coefficient of determination of 0.68, thereby demonstrating a good correlation between the modelled and observed data (Nambiar *et al*, 2020).

More recently in 2022, MethaNet provides a notable example of combining machine learning with environmental parameters to predict methane volumes from satellite images. The effective application of model inversion methods relies on the availability of high-quality data. While databases like the Emissions Database for Global Atmospheric Research (EDGAR) and the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) are valuable and accessible resources, they have faced criticism regarding data quality (Schwietzke *et al*, 2014). With suitable public data sets often unavailable, researchers frequently conduct their own trials in controlled environments to train and validate their models.

CONCLUSIONS

In summary, there are rapid advancements towards improving the capabilities of the sensors as well as to reduce the involved uncertainties in modelling greenhouse gas emission estimates. This also requires generating new databases to support these evolving models. Stakeholders must stay informed about technological advancements, model updates, and the availability of new databases. This highlights the importance of watching global trends in these areas. Staying current with these developments is critical to develop insight for an efficient approach to reducing greenhouse gas emissions in coalmines.

REFERENCES

Brandt, A R, Heath, G A, Kort, E A, O'Sullivan, F, Pétron, G, Jordaan, S M, Tans, P, Wilcox, J, Gopstein, A M, Arent, D, Wofsy, S, Brown, N J, Bradley, R, Stucky, G D, Eardley, D and Harriss, R, 2014. Methane Leaks from North American Natural Gas Systems, *Science,* 343:733–735.

Dobler, J, Braun, M, Blume, N and Zaccheo, T, 2013. A New Laser Based Approach for Measuring Atmospheric Greenhouse Gases, *Remote Sensing,* 5:6284–6304.

Fox, T A, Barchyn, T E, Risk, D, Ravikumar, A P and Hugenholtz, C H, 2019. A review of close-range and screening technologies for mitigating fugitive methane emissions in upstream oil and gas, *Environmental Research Letters,* 14:053002.

Golston, L, Aubut, N, Frish, M, Yang, S, Talbot, R, Gretencord, C, McSpiritt, J and Zondlo, M, 2018. Natural Gas Fugitive Leak Detection Using an Unmanned Aerial Vehicle: Localization and Quantification of Emission Rate, *Atmosphere,* 9:333.

Heltzel, R S, Zaki, M T, Gebreslase, A K, Abdul-Aziz, O I and Johnson, D R, 2020. Continuous OTM 33A Analysis of Controlled Releases of Methane with Various Time Periods, Data Rates and Wind Filters, *Environments,* 7:65.

Hendrick, M F, Ackley, R, Sanaie-Movahed, B, Tang, X and Phillips, N G, 2016. Fugitive methane emissions from leak-prone natural gas distribution infrastructure in urban environments, *Environmental Pollution,* 213:710–716.

Jacob, D J, Turner, A J, Maasakkers, J D, Sheng, J, Sun, K, Liu, X, Chance, K, Aben, I, McKeever, J and Frankenberg, C, 2016. Satellite observations of atmospheric methane and their value for quantifying methane emissions, *Atmospheric Chemistry and Physics,* 16:14371–14396.

Lamb, B K, McManus, J B, Shorter, J H, Kolb, C E, Mosher, B, Harriss, R C, Allwine, E, Blaha, D, Howard, T, Guenther, A, Lott, R A, Siverson, R, Westberg, H and Zimmerman, P, 1995. Development of Atmospheric Tracer Methods To Measure Methane Emissions from Natural Gas Facilities and Urban Areas, *Environmental Science and Technology,* 29:1468–1479.

Li, Y, Li, Z, Zhang, Z, Chen, L, Kurkute, S, Scaff, L and Pan, X, 2019. High-resolution regional climate modeling and projection over western Canada using a weather research forecasting model with a pseudo-global warming approach, *Hydrology and Earth System Sciences,* 23:4635–4659.

Nambiar, M K, Robe, F R, Seguin, A M, Endsin, M and Aliabadi, A A, 2020. Diurnal and seasonal variation of area-fugitive methane advective flux from an open-pit mining facility in northern Canada using WRF, *Atmosphere,* 11:1–26.

Safitri, A, Gao, X and Mannan, M S, 2011. Dispersion modeling approach for quantification of methane emission rates from natural gas fugitive leaks detected by infrared imaging technique, *Journal of Loss Prevention in the Process Industries,* 24:138–145.

Schwietzke, S, Griffin, W M, Matthews, H S and Bruhwiler, L M P, 2014. Global Bottom-Up Fossil Fuel Fugitive Methane and Ethane Emissions Inventory for Atmospheric Modeling, *Acs Sustainable Chemistry and Engineering,* 2:1992–2001.

Shah, A, Ricketts, H, Pitt, J R, Shaw, J T, Kabbabe, K, Leen, J B and Allen, G, 2020. Unmanned aerial vehicle observations of cold venting from exploratory hydraulic fracturing in the United Kingdom, *Environmental Research Communications,* 2:021003.

Sherwin, E D, El Abbadi, S H, Burdeau, P M, Zhang, Z, Chen, Z, Rutherford, J S, Chen, Y and Brandt, A R, 2024. Single-blind test of nine methane-sensing satellite systems from three continents, *Atmospheric Measurement Techniques,* 17:765–782.

Sherwin, E D, Rutherford, J S, Chen, Y, Aminfard, S, Kort, E A, Jackson, R B and Brandt, A R, 2023. Single-blind validation of space-based point-source detection and quantification of onshore methane emissions, *Scientific Reports,* 13.

Wang, J, Tchapmi, L P, Ravikumar, A P, McGuire, M, Bell, C S, Zimmerle, D, Savarese, S and Brandt, A R, 2020. Machine vision for natural gas methane emissions detection using an infrared camera, *Applied Energy,* 257:113998.

Wang, Q, Pan, X T, Xing, M W, Sun, Y L and Zhao, Y, 2023. A survey of automatic gas leakage detection and quantification based on passive infrared imaging, *Kongzhi yu Juece/Control and Decision,* 38:2265–2282.

Yacovitch, T I, Herndon, S C, Pétron, G, Kofler, J, Lyon, D, Zahniser, M S and Kolb, C E, 2015. Mobile Laboratory Observations of Methane Emissions in the Barnett Shale Region, *Environmental Science and Technology,* 49:7889–7895.

Catalysing lower-carbon mining supply in Australia

M Read[1] and E O'Connell[2]

1. Acting Head of Sustainability, Orica Limited, Melbourne Vic 3002.
   Email: meredith.read@orica.com
2. Specialist – ESG Performance and Reporting, Orica Limited, Melbourne Vic 3002.
   Email: eloise.oconnell@orica.com

ABSTRACT

Decarbonising explosives manufacturing and catalysing low-carbon mining supply is a significant global challenge.

Low-carbon manufacturing precincts – clusters of geographically close businesses across multiple industries that share a goal of adopting firmed renewable energy and decarbonising process emissions – offer one potential solution.

In an Australian first, Orica commissioned tertiary catalyst abatement technology in 2023 to mitigate greenhouse gas (GHG) emissions at its Kooragang Island (KI) facility in New South Wales (NSW), Australia. The EnviNOx® technology (ThyssenKrupp Industrial Solutions AG, Dortmund, Germany) used reduces nitrous oxide (N_2O), a potent greenhouse gas arising as a by-product of nitric acid manufacture. As a result, mining customers in NSW are now benefitting from ammonium nitrate (AN) products that are almost 50 per cent less emissions-intensive than those Orica previously offered.

The $37 million project is a private-public partnership that has involved partners across Federal and State government, global engineering and technology vendors, local community groups and local carbon advisors to overcome financial barriers.

With the first phase of decarbonisation complete, Orica is now working on longer-term options to decarbonise ammonia production and capitalise on new opportunities across mining and energy markets. In partnership with the NSW Department for Planning and Environment, a Net Zero Study has recently been formulated for Orica's Kooragang Island site which builds on a precinct-based approach and identifies four potential pathways towards achieving net zero emissions, subject to economic viability.

This paper focuses on Orica's work to decarbonise its own operations and help catalyse low-carbon industrial precincts. Shared learnings around the business model needed to support technology innovation, government participation and policy enablers, stakeholder collaboration and project technology and impacts are also communicated.

THE DECARBONISATION IMPERATIVE

Headquartered in Australia, Orica is one of the world's largest mining and infrastructure solutions providers, and an ASX100 listed company. It produces and supplies explosives, blasting systems, mining chemicals, geotechnical monitoring, digital solutions, and other services.

For Orica to deliver on its purpose to 'sustainably mobilise the earth's resources', the company must reduce its scope 1 and scope 2 greenhouse gas (GHG) emissions and develop low-carbon products for customers. Orica's decarbonisation strategy is founded on implementing practical evidence-based initiatives, deploying mature technologies, investing in emerging technical solutions, and accessing government incentives to reduce GHG emissions in an economically sustainable manner.

Orica is committed to achieving net zero emissions by 2050. It is targeting a 30 per cent reduction in net global scope 1 and 2 emissions by 2026, on a pathway to a 45 per cent reduction by 2030, from 2019 levels. In 2023 Orica introduced an ambition to reduce scope 3 emissions by 25 per cent from a 2022 baseline. The net zero emissions ambition covers Orica's global Scope 1 and 2 emissions under their direct control, and material Scope 3 emission sources. Material means the GHG emissions arising from the Scope 3 reporting categories of purchased goods and services (category 1) and use of sold products (category 11). Achieving the net zero emissions ambition will require effective government policy frameworks, supportive regulation and financial incentives, meaningful and transparent collaboration across value chains and access to new economically viable low-carbon technologies operating at commercial scale.

Orica has also committed to a renewable electricity target that will see operations powered by 100 per cent renewable electricity by 2040, with an interim step of 60 per cent by 2030.

The mining sector is hard and expensive to abate and, paradoxically, the pace of mining exploration must accelerate to facilitate the transition to a decarbonised economy. Achieving net zero emissions cannot be done in isolation. Effective government policy frameworks, supportive regulation and financial incentives, meaningful collaboration across value chains, and access to new commercially viable low-carbon technologies at commercial scale are all required. As an example, the Australian Industry Energy Transitions Initiative (AIETI; https://www.climateworks centre.org/project/australian-industry-energy-transitions-initiative/), in which Orica participated, is a tangible collaboration across multiple stakeholder groups, aimed at forging a meaningful pathway towards industrial decarbonisation.

GREENHOUSE GAS EMISSIONS IN AUSTRALIA'S INDUSTRIAL CHEMICAL SECTOR

The industrial chemical sector (UNFCCC category 2.B) in Australia emitted 4.8 mega tonnes of carbon dioxide equivalent ($MtCO_2$-e) in 2021 (Australian Government, 2021b), representing around 1.0 per cent of Australia's total greenhouse gas emissions (Australian Government, 2021b). These emissions are material to industrial organisations and their associated supply chains, due to increasing global pressure to address climate change and demonstrate that their respective targets and commitments are being met.

Orica's industrial chemical manufacturing in Australia

Production of nitric acid generates a significant quantity of nitrous oxide (N_2O) emissions, a GHG 265 times more potent than carbon dioxide (CO_2) (Australian Government, 2022). Orica currently operates nine nitric acid plants (NAPs) globally, with N_2O emissions representing 51 per cent of total scope 1 and 2 operational emissions in 2023.

Orica has two key industrial chemical manufacturing sites in Australia, one in Kooragang Island, Newcastle, and one in Yarwun, Queensland. Together, these two sites contribute approximately 31 per cent of Australia's total industrial chemical emissions. Orica has a number of joint venture operations globally, including Yara Pilbara Nitrates on the Burrup Peninsula, WA. The Yara Pilbara Nitrates facility is operated by Yara, and not under Orica's operational control.

Orica's Kooragang Island manufacturing site operates an ammonia plant, three nitric acid plants (NAPs) and two ammonium nitrate (AN) plants. In FY2022, Orica's Kooragang Island site produced approximately 370 000 t of AN and contributed 59per cent of Orica's gross overall scope 1 and 2 GHG emissions, approximately 1154 $ktCO_2$-e per annum.

Prior to the installation of tertiary abatement technology, around 24 per cent of Australia's industrial chemical sector's GHG emissions came directly from Orica's manufacturing plant at Kooragang Island (Australian Government, 2021b).

KOORAGANG ISLAND DECARBONISATION PROJECT

Orica supplies 85 per cent of the Hunter region's mines with ammonium nitrate, playing an important role in supporting mining, quarrying and construction across NSW and the supply of critical raw materials needed to drive Australia's net zero economy ambition.

To decarbonise its operations in 2023, Orica constructed and installed tertiary catalyst abatement technology at its three NAPs on Kooragang Island in an Australian-first.

The transformational KI Decarbonisation Project involved a public-private partnership with the Australian Government (ACCU Scheme), NSW Government (financial grant) and the Clean Energy

Finance Corporation (sustainable finance). Costing $37 million, it is one of Australia's largest industrial decarbonisation projects.

Orica's partnership with global technology vendor ThyssenKrupp Industrial Solutions provided access to state-of-the-art EnviNOx® technology and engineering services to ensure successful installation. According to ThyssenKrupp Industrial Solutions, the European Union authorities declared this technology to be Best Available Technique (BAT) for permitting purposes within the EU (ThyssenKrupp Industrial Solutions, 2022).

The technology is much like a catalytic converter and exhaust system on a car, destroying combustion emissions and protecting air quality. The technology features catalyst beds filled with iron zeolite catalysts, located in a reactor between the final tail gas heater and the tail gas turbine. This results in almost complete decomposition of N_2O into its elements, nitrogen and oxygen (ThyssenKrupp Industrial Solutions, 2022).

Ongoing demonstrated performance of the technology is monitored and measured as the business model for the Kooragang Island Decarbonisation Project includes contractual obligations to achieve the forecast emissions reduction outcomes.

Environmental and social performance

For target-setting purposes, Orica established a baseline year of 2019 for operational scope 1 and 2 emissions. Thus, a baseline for the KI Nitrates Decarbonisation Project was set on the basis of 2019 reported emissions for the purposes of internal performance monitoring. This was pre-final investment decision on the project, and representative of business-as-usual performance if the project had not occurred. In the baseline period, 51 per cent of the site's GHG emissions were N_2O from the nitric acid plants. Consecutive installation across the plants over 12 months to June 2023 eliminated more than 350 000 tCO_2-e, abating nitrous oxide emissions from the three NAPs on-site by at least 98 per cent. Due to the efficacy of the EnviNOx® technology in eliminating N_2O emissions, the site's GHG footprint was almost halved as a result of the project.

In full operation, this catalyst abatement technology will continue to eliminate approximately 500 000 tCO_2-e each year. As shown in Figure 1, this is equivalent to 48 per cent of the site's total GHG emissions and 11 per cent of all chemical industry process emissions in Australia (Australian Government, 2021b).

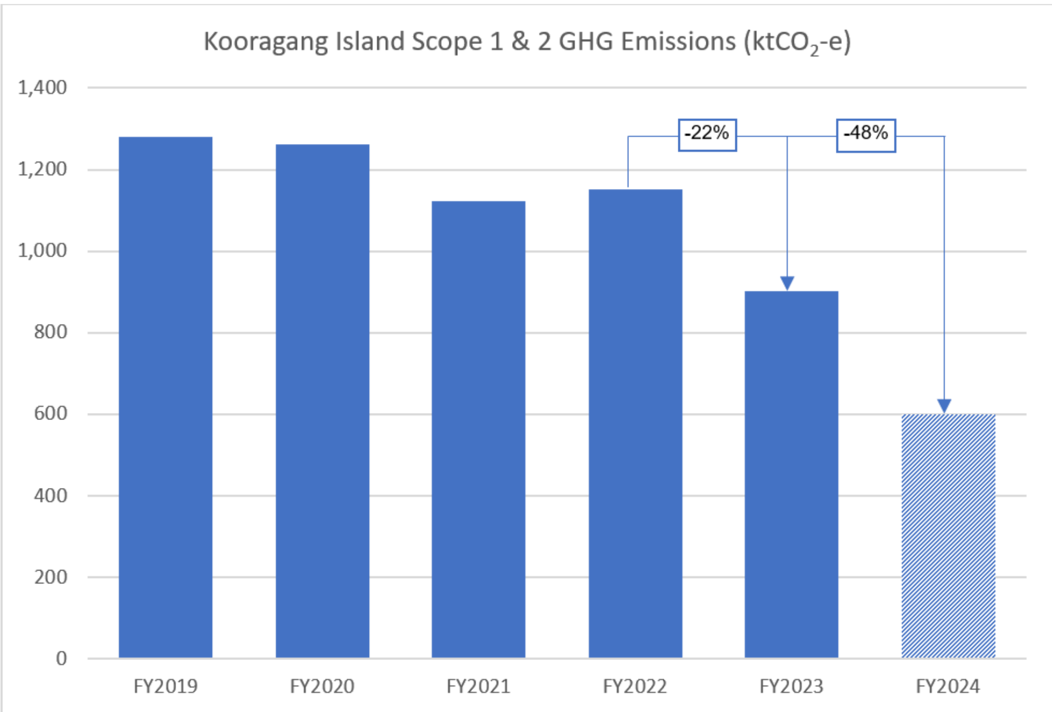


FIG 1 – Reducing emissions at Kooragang Island. Note: FY24 is a forecast.

Another significant outcome is that the AN products Orica delivers mining customers from KI are now almost 50 per cent less emissions intensive than before, thus contributing to a reduction in their Scope 3 emissions.

In addition to the direct environmental outcomes, lower-carbon manufacturing has improved Orica's ESG value proposition to employees, with indirect benefits relating to employee engagement and talent retention.

Local economic benefits

Together with environmental outcomes, the project is delivering economic benefits to the Hunter region of NSW. Approximately one third (34 per cent) of the $37 million project was spent with local NSW suppliers, and of this two-thirds (67 per cent) went to suppliers in the Hunter Valley (AIGIS Group, 2021). Local spend occurred in areas such as site development, piping, electrical instruments and controls, local engineering and installation expertise, and bulk construction items procured through local NSW agents.

This injected an additional $12.4 million into the economy (not taking into account any multiplier effects of this capital expenditure spend).

A NEW BUSINESS MODEL TO SUPPORT DECARBONISATION

Decarbonisation and tertiary abarement projects often face financial barriers and disincentives because they don't deliver a direct commercial return in terms of operational efficiencies.

Orica's KI decarbonisation project overcame this by replicating a collaborative business model that was successfully proven at its Carseland manufacturing plant in Alberta, Canada. A $37 million private-public partnership was forged across federal and state government agencies and regulators, global engineering and technology vendors, local community groups and local carbon advisors. The business model spanned carbon market development, carbon contracting, transition finance and technology performance.

Carbon market development

Participating in carbon markets and originating carbon credits through transformational and additional emissions avoidance activity can offer a return on capital. The Australian Emissions Reduction Fund (ERF) (now known as the ACCU Scheme) was identified as a suitable regulatory scheme in which tertiary catalyst abatement qualified for registration.

Following completion of initial project engineering, Orica developed the business case for the KI Decarbonisation Project and applied to the ERF for it to be registered as an eligible carbon credit project.

The project was approved in March 2021 by the Clean Energy Regulator, under the ERF's Facilities method, to participate in Australia's carbon market through the generation of Australian carbon credit units (ACCUs). While a number of methods exist for energy efficiency initiatives, the Facilities method 'provides a high-level, activity-neutral framework to calculate abatement from facilities that report under the National Greenhouse and Energy Reporting (NGER) scheme' (Australian Government, 2021a). Registration under the Facilities method provided a mechanism for the KI facility to earn ACCUs for improvements in emissions intensity over seven years across one or more production variables, in this case ammonia and ammonium nitrate production.

Carbon contracting

While originating carbon credits gives rise to a new financial asset, the units are exposed to market dynamics and price fluctuations. This uncertainty is unwanted in making any capital investment decision. Further, while a commercially viable business case was required, the focus of the project was on delivering an emissions reduction outcome, and hence there was minimal incentive to seek returns through open market trading. One mechanism to establish price certainty is to secure long-term offtake agreements. In this case, the Australian Government's reverse carbon auctions were identified as an effective way to secure this offtake, helping to underwrite the project.

The KI Decarbonisation Project successfully participated in the April 2021 auction and was awarded the first optional carbon abatement contract under the facilities method for the purchase of around 3.4 million ACCUs by the Australian Government. This project represents the largest industrial ERF project in the last three years, and the tenth largest ERF carbon abatement contract ever.

Transition finance

Orica applied for grant funding through the High Emitting Industries Fund offered by the New South Wales Government's Net Zero Industry and Innovation Program and was awarded a co-investment of $13.06 million. Together with Orica's $24 million contribution the project's economic viability was improved.

In addition, Orica secured financing through the Federal Government's Clean Energy Finance Corporation (CEFC). The CEFC provided a $25 million debt finance facility to fund Orica's capital contribution to the Kooragang Island Decarbonisation Project. This debt instrument is linked to successful attainment of emissions reduction KPIs, outcomes and performance targets.

This project was the first major direct investment by the CEFC in the manufacturing sector, it also represents one of the largest single abatement projects financed by the CEFC to date.

CATALYSING LOWER-CARBON MINING SUPPLY CHAINS

Following the success of the KI Decarbonisation Project, and the business model described above, Orica is installing the same technology in two plants at its Yarwun facility in Gladstone in 2024. It is estimated that the Yarwun Nitrates Decarbonisation Project will reduce the site's gross scope 1 emissions by 200 000 tCO_2-e per annum and abate a total of 1.5 $MtCO_2$-e by 2030.

Further, two of Orica's peers in the industry have also announced similar projects for the installation of tertiary catalyst abatement and have similarly leveraged Australian carbon market opportunities to help build a case for the capital investment.

Additional benefits of the partnership with the New South Wales Government are also being realised through agreed knowledge sharing obligations under the funding agreement, and a commitment for Orica to share key learnings from the project in the interest of further decarbonisation of hard-to-abate sectors.

A LONG-TERM, PRECINCT-BASED APPROACH

The NSW Government has identified that supporting the decarbonisation of the region's mining and manufacturing industries is vital to achieving its legislated goal of net zero by 2050. As a result, the Hunter Valley is now the proposed home to low-carbon manufacturing precincts where clusters of geographically close businesses across multiple industries share a goal of adopting renewable energy and decarbonising process emissions.

This precinct-based approach, coupled with the success of a large foundational abatement project has given Orica the confidence to invest further in decarbonisation more broadly and specifically in the Hunter Valley, and to pursue market and customer diversification opportunities.

Orica continues to invest in several significant partnerships and innovations in parallel in the region, and in 2023, completed a Net Zero study for the Kooragang Island facility, in further partnership with the NSW Government. The study validated a roadmap outlining the major activities and decisions to transition the Kooragang Island asset to net zero scope 1 emissions, subject to economic viability. It identified four potential pathways, as shown in Figure 2. These pathways will be further investigated as the roadmap is implemented, and Orica is currently progressing a number of early actions in pursuit of this. Based on early assessments, renewable hydrogen was identified as the most viable pathway.

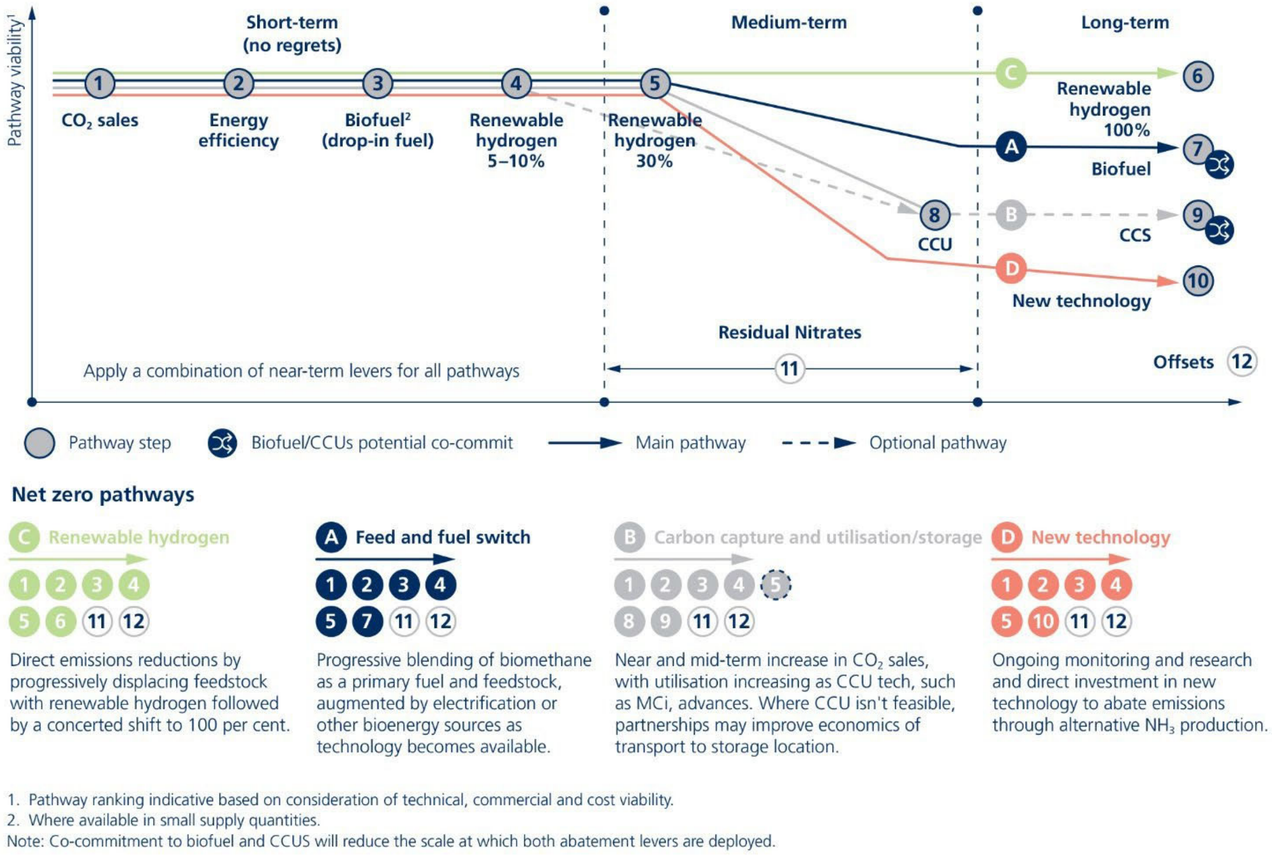


FIG 2 – Pathways identified in the Kooragang Island Net Zero Study.

Establishing a renewable hydrogen and lower-carbon ammonia export industry

Orica and Origin Energy are joint partners in the development of commercial scale renewable hydrogen production and associated value chains in the Hunter Valley. The Hunter Valley Hydrogen Hub (HVHH) will produce renewable hydrogen via electrolysis using recycled water, renewable electricity and grid-connected electrolysers. Renewable hydrogen will be integrated into Orica's existing Ammonia Manufacturing Facility (AMF) at KI to produce low carbon ammonia products for existing customers and for supply to new hydrogen and ammonia markets.

HVHH has been shortlisted to potentially receive a share of the Australian Renewable Energy Agency's (ARENA) A$2 billion Hydrogen Headstart funding. The project capitalises on Orica's existing infrastructure and the Hunter Region's skills base to deliver the fastest, lowest risk and most practical route to establishing a renewable hydrogen and ammonia industry.

HVHH will install 250 MW of electrolysis across its first two phases, with phase one to deliver approximately 4700 t per annum of renewable hydrogen. The HVHH's renewable hydrogen will displace natural gas used as feedstock in the production of ammonia and ammonium nitrate, with subsequent project phases to further scale this displacement.

The project is being designed with the potential to be scaled up to an export development in the future, providing employment growth opportunities and further energy diversification for the region.

Developing a carbon capture, usage and storage (CCUS) solution through a long-term joint venture with Mineral Carbonation International (MCi)

Orica's long-term joint venture with Mineral Carbonation International (MCi) (now MCi Carbon), focused on commercialising CCUS technology, won 'Best Clean Energy Startup' at COP 26 in Glasgow. A $14.6 million Australian Government grant is supporting a CCUS demonstration plant being built by MCi at Kooragang Island. When operational in 2025 it will have the capability to capture 1000 tCO_2-e per annum generated from Orica's ammonia plant and offers the opportunity to confirm the scale-up potential of this technology.

CONCLUSIONS

Orica has proven that with the right corporate commitment, partnerships and policy settings, demonstrable emissions reduction is possible in hard and expensive to abate sectors of the economy.

Collaboration with peers, governments, customers, and industry to better understand and develop economically sustainable pathways towards a decarbonised future is critical. As such, Orica continues to support national and sub-national government efforts to implement effective policy frameworks to support decarbonisation that would be otherwise uneconomical.

A long-term, precinct based-approach can also help forge a path towards a net zero future. Orica's ambitious approach, as demonstrated by the initiatives underway at KI, will enhance business operations and performance and benefit customers by enabling more sustainable procurement.

This will directly reduce the scope 3 emissions of the vital industries Orica supplies, helping to forge a robust, low-carbon future for sectors underpinning the Hunter economy.

ACKNOWLEDGEMENTS

Orica would like to acknowledge the collaborative partnership, support and where relevant, financial contributions offered by the NSW Government, Clean Energy Finance Corporation, ThyssenKrupp Industrial Solutions, and suite of corporate advisors including Ndevr Environmental (now Anthesis Australia), Tasman Environmental Markets, Herbert Smith Freehills and Ashurst.

REFERENCES

AIGIS Group, 2021. Orica Kooragang Island Economic Effects Analysis.

Australian Government, 2021a. Facilities method, Clean Energy Regulator, Emissions Reduction Fund. Available from: <https://www.cleanenergyregulator.gov.au/ERF/Choosing-a-project-type/Opportunities-for-industry/facility-methods/facilities-method>

Australian Government, 2021b. UNFCCC emissions (AR4), Department of Climate Change Energy, the Environment and Water, Australia's National Greenhouse Accounts. Available from: <https://greenhouseaccounts.climatechange.gov.au/>

Australian Government, 2022. National Greenhouse and Energy Reporting, Global Warming Potentials, Clean Energy Regulator. Available from: <https://www.cleanenergyregulator.gov.au/NGER/About-the-National-Greenhouse-and-Energy-Reporting-scheme/global-warming-potentials>

ThyssenKrupp Industrial Solutions, 2022. EnviNOx - reduce NOx emissions to a minimum. Available from: <https://www.ThyssenKrupp-uhde.com/en/products-and-technologies/fertilizer-technologies/nitrate-plants/nox-reduction-with-envinox>

The hidden path to sustainable mining – an incentive for transforming scope 3 emissions across industries

N Shahbazi[1] *and K Sherry*[2]

1. Senior Environmental Advisor – Advisory, RPMGlobal, Brisbane Qld 4000.
   Email: nshahbazi@rpmglobal.com
2. Principal Environmental Advisor – Advisory, RPMGlobal, Brisbane Qld 4000.
   Email: ksherry@rpmglobal.com

ABSTRACT

Scope 3 emissions are a set of often overlooked indirect greenhouse gas emissions within a company's value chain and represent the majority of emissions for many sectors. These emissions arise from activities conducted by entities beyond the reporting organisation's ownership or direct control and are often challenging to calculate. Scope 3 emissions typically encompass purchasing goods and services, transportation and distribution, managing operational waste, downstream processing and utilising sold products. Within the mining sector, scope 3 emissions often constitute a significant portion of the overall carbon footprint. Therefore, these emissions are a significant aspect of the future of sustainable mining. As the journey towards a world committed to achieving Net Zero Emissions has started, the time to spark a transformative conversation in the mining industry has arrived. Consequently, a better knowledge of scope 3 footprints allows organisations to assess their emission mitigation projects against the total carbon impact of their operations and products.

This presentation aims to achieve two main goals. Firstly, uncover the extent of scope 3 emissions in the mining sector. Secondly, demonstrate that mining's carbon footprint is felt across every industry's scope 3 emissions, highlighting the importance of an accurate understanding of mining product total emissions, including upstream scope 3. In addition, the challenges in estimating scope 3 emissions and areas for improvement are explored through case studies, which highlight the difficulties in assessing scope 3 emissions in the mining industry and suggest ways to enhance the practice.

The mining industry across Australia operates within a broad sustainability reporting framework, and the recent shifts toward sustainability and environmental responsibility require the inclusion of scope 3 emissions within this framework. Therefore, the Australian Government Department of the Treasury has developed a sustainable finance framework for large businesses. This framework aims to enhance greenhouse gas (GHG) reporting transparency, standardising and improving the quality of climate-related financial disclosure reporting. This aligns the Task Force on Climate-related Financial Disclosures (TCFD) recommendations with the International Financial Reporting Standards (IFRS) S2 Climate-related Disclosure issued by the International Sustainability Standards Board (ISSB). The imposed reporting is to align with global trends toward corporate environmental responsibility and transparency.

Under this framework, entities must disclose their absolute scope 1, 2, and 3 emissions. They are also required to categorise the sources of scope 3 emissions based on the 15 categories listed in the IFRS S2 definitions. Reporting is scheduled to commence for large entities from 2025–2026 onward, with the limited assurance of scope 3 emissions. Meanwhile, mining companies can proactively address scope 3 emissions to prepare for regulatory mandates and mitigate potential compliance risks.

Understanding the calculation methods for scope 3 emissions and accurately quantifying them is critical for companies to identify their emissions hotspots, set reduction targets, and implement effective mitigation measures.

Scope 3 emissions are calculated using allocation metrics primarily in the physical consumption of products. Allocation becomes necessary when a single system produces multiple outputs, and emissions are evaluated for the entire system. It is essential for companies to choose the allocation

method that most accurately reflects the link between the output production and their resulting emissions, ensuring accurate estimates.

The integration of both primary and secondary data is essential to comprehensively understand an entity's scope 3 emissions. Primary data, acquired directly from the value chain, includes information on energy consumption, waste generation, and transport logistics. Suppliers and customers play a crucial role in providing this primary data, which is vital for accurately measuring scope 3 emissions. On the other hand, secondary data offers a broader context through emission factors obtained from industry reports, governmental databases, or academic research. While secondary data, such as industry averages, can provide initial insights, it may not reflect the specific realities of an entity's operations and should, therefore, only serve as a supplementary resource. For a truly accurate and actionable understanding of scope 3 emissions, which is necessary for developing effective emission reduction strategies, reliance on primary data is crucial. This comprehensive approach requires collaboration across operations, suppliers, and the entire value chain.

The carbon footprint generated by mining operations has significant and enduring effects on various industries by influencing their scope 3 emissions. Understanding the total emissions associated with mining products, including their upstream scope 3 emissions, is essential for all industries to accurately calculate their emissions. Accounting for these emissions is crucial for organisations across all sectors to effectively address and mitigate their greenhouse gas emissions and environmental impacts. Consequently, the objective of understanding the scope 3 emissions of the mining sector extends far beyond the mining industry, impacting the carbon footprint calculations and reduction efforts of all other sectors within the value chain. This understanding of the scope 3 emissions of mining can enhance reporting and regulatory compliance while also opening doors and paving the way for future projects. As a result, the mining sector can better position itself to meet the transparency requirements of implementing the Australian Treasury's Climate-related financial disclosure legislation concerning their own Environmental, Social and Governance (ESG) obligations.

This presentation highlights the importance of early understanding of scope 3 activities, using case studies to demonstrate the challenges and opportunities ahead of the Australian government legislation in 2026. The case studies reveal key challenges mining companies may face when incorporating scope 3 data collection and reporting into their operations. Companies that begin discussions with their supply chain partners early to share data will find scope 3 reporting easier and more effective. Understanding and managing scope 3 GHG emissions is crucial for meeting sustainability goals and reinforcing the mining sector's commitment to ESG improvement. Engaging with suppliers and customers to use primary data allows mining companies to set credible targets and develop effective emissions reduction strategies, enhancing transparency and community trust. The mining sector's influence on scope 3 emissions across various industries underscores the importance of comprehensive emission accounting in supporting global sustainability efforts.

Advancing sustainability in pumping systems – a comprehensive methodology for calculating, monitoring and minimising power and water consumption

A Varghese[1,4], S Martins[2], E Lessing[3], G M Hassan[5] and A Karrech[6]

1. Product Head – Pumps Digital, Metso, Perth WA 6110. Email: alan.varghese@metso.com
2. Research and Development Engineer, Metso, Montreal QC H8S 2R9, Canada. Email: sudarshan.martins@metso.com
3. Vice President Engineering – Pumps, Metso, Espoo 02230, Finland. Email: evert.lessing@metso.com
4. PhD Student, University of Western Australia, Perth WA 6009. Email: alan.varghese@research.uwa.edu.au
5. Senior Lecturer, University of Western Australia, Perth WA 6009. Email: ghulam.hassan@uwa.edu.au
6. Professor, University of Western Australia, Perth WA 6009. Email: ali.karrech@uwa.edu.au

ABSTRACT

Pumps play a critical role in mining operations, and their energy consumption and environmental impact are significant. This paper addresses the need for a holistic approach to sustainable pump deployment by expanding on previous work presented at IMPC Asia Pacific 2022 and World Mining Congress 2023. The research takes a significant step forward by outlining a structured approach to estimate and demonstrate sustainability tailored for operational slurry pumps. It details the calculation methodologies used to quantify the carbon dioxide emissions from electricity, wear materials and transport, as well as sealing water usage. To enhance practicality and usability, a simplified visual representation—called sustainability metrics—has been developed to monitor overall efficiency. The sustainability metrics consist of the availability, pump efficiency, and water utilisation efficiency. The proposed methodology is integrated with Pumps Condition Monitoring Service to maximise benefits. Three case studies, from iron ore, copper, and nickel operations globally, were employed to evaluate the proposed methodology. The findings demonstrate the critical role of sustainability calculations in understanding pumps operation. These calculations improve awareness of the pump's role in the sustainability journey and enable effective monitoring. The studies highlight that continuous monitoring paired with effective prescriptive maintenance strategy can significantly reduce power and water consumption while maximising pump availability. The case studies also reveal significant shortcomings in current operational practices and non-optimal maintenance regimes, emphasising the need for practical recommendations to maximise savings and optimise pump performance. In the context of increasing climate change awareness and the imperative for global decarbonisation, this research highlights the necessity of critically assessing methods and operations to drive sustainability in the mining industry. By adopting a holistic approach to sustainable pump deployment, mining operations can effectively reduce their environmental impact while enhancing operational efficiency and economic viability. The proposed methodology and case studies provide valuable insights and practical recommendations for mining companies seeking to achieve sustainable practices and contribute to a decarbonised future.

INTRODUCTION

Sustainability has become a key priority across mining and mineral processing industry, prompting the need for robust methodologies to evaluate and benchmark environmental impact. Most efforts are focused on large comminution equipment, while ancillary equipment like pumps has received much less attention. Although, the size of an individual pump may be relatively small, the sheer number of pumps deployed across a mine site collectively adds up, making it essential to understand their sustainability impact. This paper builds upon prior research presented at IMPC Asia Pacific 2022 and the World Mining Congress 2023, emphasizing the need for pumps to receive equal attention in the sustainability journey. As the past papers highlight, there are presently no methods used to calculate the sustainability of pumps in mining industry.

This paper takes a significant step forward by outlining a structured approach to estimate and demonstrate sustainability tailored for slurry pumps. The proposed methodology considers the environmental impact across the entire pump 'use' cycle. It explains the carbon dioxide (CO_2) emissions from electricity consumption, wear materials manufactured, and transportation to the mine site. Additionally, the methodology includes sealing water usage in pump operation, specifically focusing on water management. Furthermore, simplified sustainability metrics with overall efficiency is developed that incorporates availability, water utilisation efficiency and pump efficiency.

Three case studies from iron ore, copper, and nickel operations globally are employed to evaluate the proposed methodology. These case studies aim to not only demonstrate the methodology but also to identify potential shortcomings in current operational practices and highlight areas where non-optimal maintenance regimes might be hindering sustainable pump operation. The proposed methodology should be applied together with Pumps Condition Monitoring Service (PCMS) to track and optimise the pump condition and maximise sustainability.

PUMPS SUSTAINABILITY CALCULATION METHODOLOGY

A systematic calculation methodology has been developed to assess sustainability of slurry pumps in operation. The proposed methodology draws inspiration from ISO 14067, a standard that guides the quantification, monitoring, and reduction of a product's carbon footprint. The authors have adapted this framework to evaluate the carbon footprint of slurry pumps, focusing on the 'use' phase. In this context, the CO_2 emissions originate from electricity consumption, wear materials and transport. Further, to complete a holistic view of the sustainability of pumps, the authors also deemed it necessary to include the water consumption needed for shaft sealing. Most shaft sealing methods require water usage which leads to a certain amount being lost to the environment. The aim is to quantify this water wastage in combination with the aforementioned carbon footprint to assess the sustainability of slurry pumps.

Electricity emissions

Firstly, to calculate the CO_2 emissions from electricity the yearly power consumption needs to be determined using absorbed power of the pump within its annual run hours. Later, apply the electricity emission factor specific to the region. For instance, in Australia, the emission factor is 0.97348 kg CO_2/kWh (Ecoinvent, 2020). By multiplying the yearly power consumption by the electricity emission factor, the pump electricity emissions can be calculated in kilograms.

Wear materials emissions

Secondly, wear parts in slurry pumps require timely replacement. These parts include wet end components (eg impeller, casing, liners) and other spare parts (eg gland packing, lantern rings, bearings). The availability of the pump, achieved by minimising downtime, is crucial for users. However, this focus on uptime can occasionally lead to underutilisation of wear materials, resulting in material wastage. Usually, if the material is metal, it can be recycled. Wet end metal components are typically made of white iron alloys, which are expensive. Recycling these materials can result in significant cost savings and environmentally friendly options. On the other hand, rubber materials have a limited shelf life, are generally very damaged by the slurry particles and not considered for recycling. To estimate CO_2 emissions, the authors consider the materials consumed (in kilograms per annum) without the possibility of recycling. The CO_2 emissions factor for metal and rubber are 1.85 tons CO_2/ton steel and 2.74 kg CO_2/kg rubber respectively (Ecoinvent, 2020).

Transport emissions

Transport emissions account for material movement from logistics facilities to the site. This includes both material mass and distance travelled. The number of wear parts used has direct correlation to the mass moved. The authors have used a CO_2 emission factor of 3.90E-05 kg CO_2/km for this purpose (Ecoinvent, 2020).

Water usage

Sealing water usage is driven by two factors; first the type of gland sealing arrangement used eg full flow gland seal, or reduced water sealing like Enviroset™, secondly the correct setting or maintenance of the chosen sealing arrangement eg a poorly set or maintained full flow gland seal can consume multiple times a properly set and maintained full flow gland seal. For reference, in this paper, the authors use the published water consumption for properly set and maintained sealing arrangements.

DIGITALISATION AS AN ENABLER

In the pursuit of sustainability in mining, digitalisation has emerged as a powerful enabler. According to Barnewold and Lottermoser (2020), Digitalisation in mining refers to use of computerised or digital devices or systems and digitised data that are to reduce costs, improve business productivity, and transform mining practices.

Digitalisation empowers sustainability in various ways, such as utilising data to develop and monitor metrics that assess the sustainability performance of pumps. Using PCMS enhances visibility into pump health, gathering valuable insights that enable proactive maintenance. Other strategies for maximising digitalisation includes adding sensors (such as pressure transmitters, flow metres and slurry density instruments) wherever possible, establish decision framework to act upon actionable information and have sustainability champions who can maintain and drive these initiatives forward (Varghese *et al*, 2022). By leveraging digital technologies, mining operations can achieve prompt decision-making, accurate data analysis, and better collaboration—all while minimising power consumption, time, and noise pollution.

Digitalisation and sustainability are deeply connected and becomes increasingly evident as process optimisation inherently leads to resource efficiency and reduced environmental impact. Hence, this powerful combination allows mining operations to visualise their sustainability efforts and actively shape the future of the mining industry.

Sustainability metrics

Leading on from the previous section which quantifies the sustainability of slurry pumps in context of the carbon footprint and water usage, the authors developed the following metrics to score the sustainability of slurry pumps. They evaluate the pumps according to their availability to work, how good they are at conserving water, and how well they use energy.

At time t, the operating state of the pump is defined as:

$$x(t) = \begin{cases} 0, when\ in\ maintenance\ at\ time\ t \\ 1, when\ in\ operation\ at\ time\ t \end{cases}$$

With a large population of operating states, the availability A of the pump can be determined. The availability is defined as the probability of finding the pump in a functional state.

$$A \stackrel{\text{def}}{=} \Pr\,[x = 1]$$

It is assumed that wear drives most of the maintenance activities both for planned and breakdown maintenance. For duty only pumps breakdowns are much more disruptive than for a standby/duty pump arrangement where a quick switchover to the standby pump guarantees high availability. Consequently, for the duty only pump arrangements the availability is largely driven by premature wear breakdowns.

The water efficiency of the pump is a function of the volume of water lost to the seal (q) with respect to the total volumetric flow in the pump (Q). The pump water efficiency decreases as more water is lost to the seal. Note, ReLU is the rectified linear unit function.

$$\eta_{H_2O} \stackrel{\text{def}}{=} ReLU(1 - \frac{q}{Q})$$

Finally, the pump energy efficiency is a ratio between the hydraulic power generated and the power draw P. The hydraulic power is a product of the slurry density ρ, the gravitational constant g, the volumetric flow Q, and the head H.

$$\eta_E = \frac{\rho g Q H}{P}$$

It is important to remember that the energy efficiency of the pump deteriorates over time, as the various hydraulic parts wear, translating into additional energy consumption. Therefore, the energy efficiency also captures wear to some degree.

These metrics can be consolidated into an overall efficiency, the pump sustainability efficiency, defined as:

$$\eta_S \stackrel{\text{def}}{=} \frac{1}{3}(\eta_P\, \eta_{H_2O} + A\, \eta_P + \eta_{H_2O}\, A)$$

Overall, the metrics give an indication of performance, energy efficiency, water waste, and wear as shown in Figure 1. In some sense, they touch on people, planet and profits (performance)—the definition of sustainability. These metrics must be regularly monitored, and appropriate action must be taken to keep them at their highest.

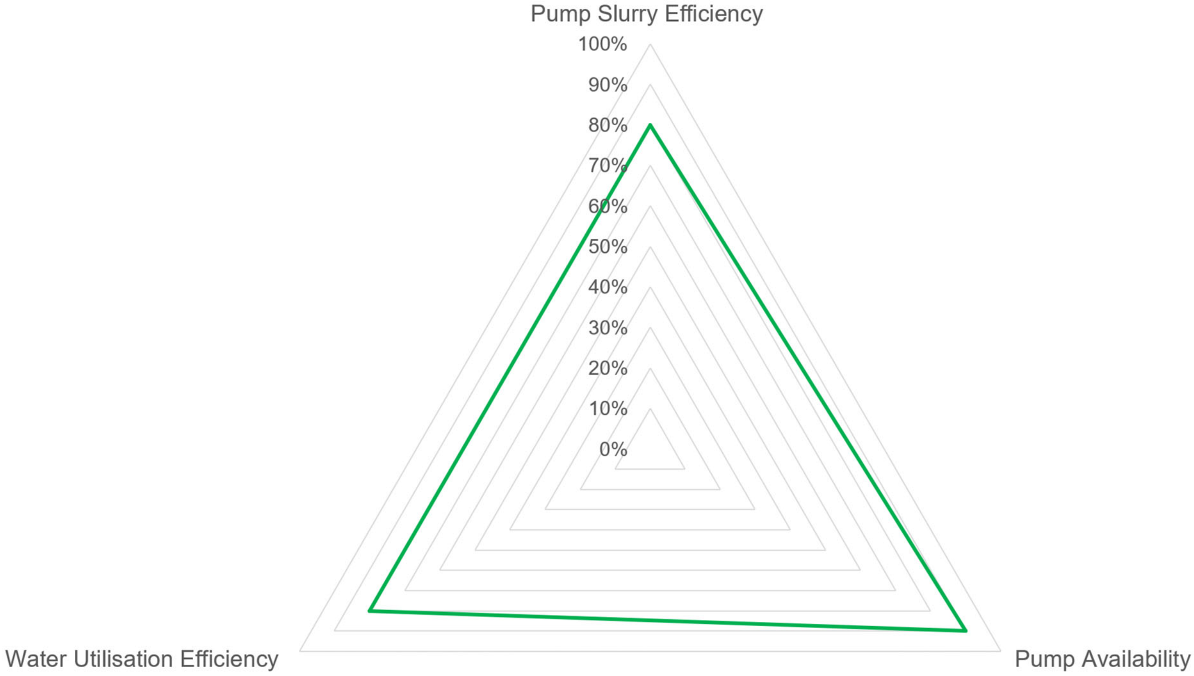


FIG 1 – The sustainability metrics.

Pumps condition monitoring service (PCMS)

PCMS is an efficient and cost-effective way to start the digitalisation and sustainability journey for pumps. Despite their common use, pumps often operate discreetly across a site, making it easy to overlook their maintenance needs. This lack of visibility can trigger a series of problems, impacting not just safety (Varghese *et al*, 2023) but also overconsumption of labour, materials and resources like energy from inefficient pumps and water from worn seals. These issues substantially add to operational costs. Moreover, unscheduled pump failures can result in substantial production losses.

PCMS enhances visibility into pump operation and enables early detection of potential equipment issues before they escalate into failures. This service offers a significant advantage by providing real-time insights to the performance and health of the pump allowing for a proactive maintenance strategy. It employs advanced detection techniques such as vibration, temperature, ultrasound, electrical and infrared thermography to create a comprehensive assessment. The emergence of low-cost and reliable wireless sensors, especially for vibration and temperature analysis has further enhanced the effectiveness of PCMS. These sensors significantly reduced the traditional labour-intensive manual route-based analysis methods, while enabling data availability within minutes. Figure 2 showcases an example of wireless sensors installed on a slurry pump in red circles. The effectiveness of PCMS is further amplified when coupled with prescriptive maintenance supported by reliability engineering expertise. This approach allows proactive management of pump conditions, optimising operations and extending pump life.

FIG 2 – Wireless sensors installed on slurry pump in red circles.

Collaboration is key to success. Majority of pump manufacturers offers some form of PCMS. These services are most effective when all key stakeholders, including pump manufacturers and the maintenance and operations departments of end-users, work collaboratively. Implementing dashboards and analysis tools is a great start to understanding pump faults. However, the key to success lies in translating these insights into appropriate actions and driving the necessary transformations.

CASE STUDIES

To assess the proposed methodology, three distinct pump cases from copper, nickel and iron ore operations globally have been selected. The summary of sustainability calculations for each case is presented in Table 1, covering electricity emissions, wear material emissions and transport emissions. For a standardised approach, the electricity emission factor of Australia and 1000 km distance from the last material dispatch has been used. Additionally, the table includes water utilisation data and sustainability metrics.

TABLE 1

Pumps sustainability calculations.

Sustainability information	Copper site		Nickel site		Iron ore
	Previous pump	**New pump**	**Original duty**	**Five years later duty**	**Large pump**
Pump Size and Type	300 Inlet Rubber	250 Inlet Rubber	250 Inlet Metal	250 Inlet Metal	550 Inlet Metal
Electricity emissions					
Yearly Pump Power Consumed, kW	552 000	405 600	1 072 000	1 984 000	4 508 000
Electricity Emission Factor (Australia) kg CO_2/kwh	0.97348	0.97348	0.97348	0.97348	0.97348
Electricity CO_2 emission, kg/annum	**537 360.96**	**394 843.49**	**1 043 570.56**	**1 931 384.32**	**4 388 447.84**
Wear materials emissions					
Pump Uptime, hrs	8000.00	8000.00	8000.00	8000.00	7752.00
Pump Downtime, hrs	0.00	0.00	0.00	0.00	248.00
Spares, Mass × Lifetime (Metal), kg/annum	2740.67	2132.00	3754.40	5005.87	20 486.00
Spares, Mass × Lifetime (Rubber) kg/annum	2008.67	1761.33	0.00	0.00	0.00
Consumption Recycled (Only Metal Parts)	1370.33	1066.00	1877.20	2502.93	10 243.00
Consumption Not Recycled (Metal Lost)	1370.33	1066.00	1877.20	2502.93	10 243.00
Consumption Not Recycled (Rubber Lost)	2008.67	1761.33	0.00	0.00	0.00
CO_2 Emission Factor (Metal)	1.85E+00	1.85E+00	1.85E+00	1.85E+00	1.85E+00
CO_2 Emission Factor (Rubber)	2.74E+00	2.74E+00	2.74E+00	2.74E+00	2.74E+00
CO_2 Consumption (Metal)	2535.12	1972.10	3472.82	4630.43	18 949.55
CO_2 Consumption (Rubber)	5.50E+03	4.83E+03	0.00E+00	0.00E+00	0.00E+00
Materials CO_2 emission Total, kg/annum	**8038.86**	**6798.15**	**3472.82**	**4630.43**	**18 949.55**
Transport emissions					
Distance From Last Material Dispatch, km	1000.00	1000.00	1000.00	1000.00	1000.00
Material Mass, kg	4749.33	3893.33	3754.40	5005.87	20 486.00
CO_2 Emission Factor	3.90E-05	3.90E-05	3.90E-05	3.90E-05	3.90E-05
Transport CO_2 emission, kg/annum	**185.22**	**151.84**	**146.42**	**195.23**	**798.95**
Water utilisation					
Gland Water Used, L/s	0.70	0.17	0.75	0.75	0.53
Yearly Water Utilised by pump, m^3	20 160.00	4800.00	21 600.00	21 600.00	15 360.00
Sustainability metrics					
Pump Slurry Efficiency η_E	49%	67%	71%	71%	79%
Pump Availability A	100%*	100%*	100%*	100%*	97%
Water Utilisation Efficiency η_{H_2O}	69%	83%	83%	83%	90%
Overall Sustainability Efficiency η_S	51%	69%	71%	71%	78%

**Estimated 100% availability when duty/standby pump set-up.*

Copper site – right pump size for sustainability gains

The case study of pump application at copper site explains how selecting the right pump size can significantly improve sustainability gains. Originally, this application had a 300 mm inlet pump that was oversized for the duty. Subsequently, it was replaced with smaller 250 mm inlet pump. Both pumps were rubber lined and had a metal impeller. The calculation demonstrates that using correct size pump significantly reduce yearly power consumption and electricity emissions. The decrease is attributed to the smaller pump's higher efficiency of 67 per cent, compared to original pump's 49 per cent by operating closer to Best Efficiency Point (BEP).

Beyond energy savings, wear material emissions primarily from spare parts usage have also reduced by using the smaller pump. This reduction is due to smaller pump operating better for the application and having reduced material weight. Similarly, transportation emissions are minimised due to smaller weight and size. Overall, this case study demonstrates 36 per cent reduction in electricity emissions, 18 per cent decrease in wear material emissions and 22 per cent drop in transport emissions. Additionally, the sustainability metrics presented in Figure 3 easily illustrates the savings and allows to track the pump sustainability measure for future.

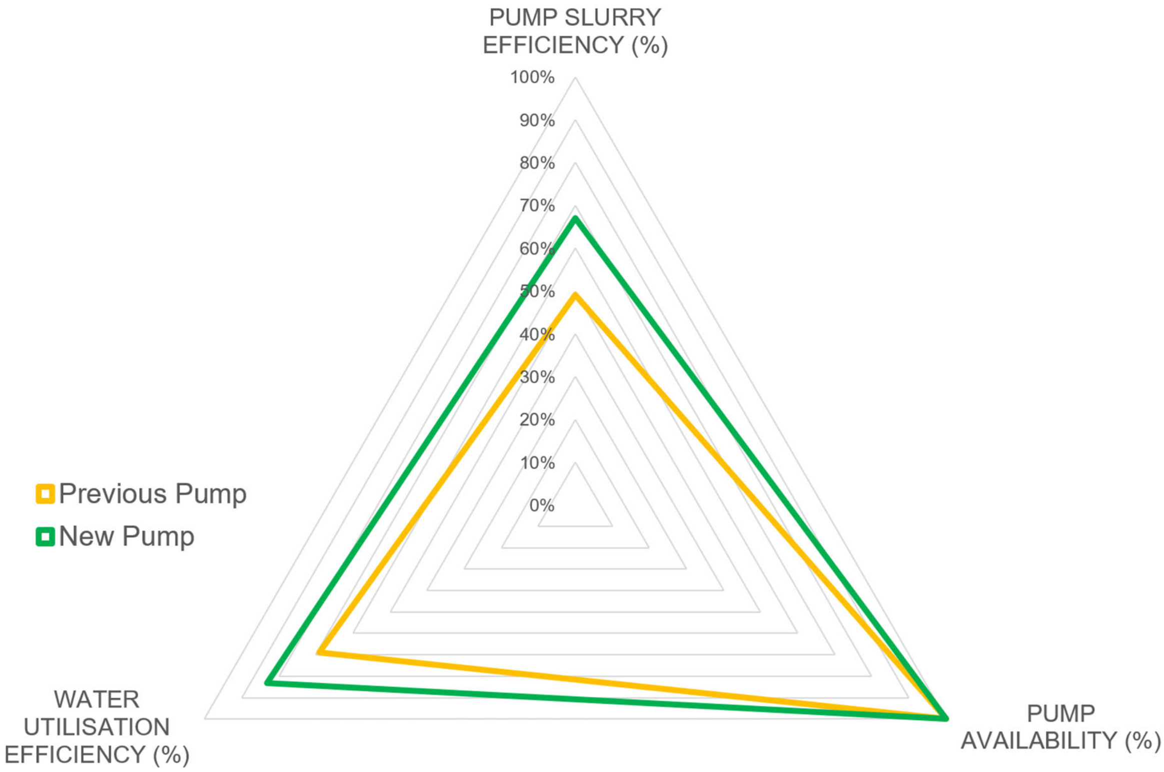


FIG 3 – Sustainability metrics for copper site pump application.

Nickel site – evolving duties and necessity of continuous monitoring

Mining operations often increases its production year-on-year, and the pump needs to adapt to this evolving duty over the time. After a certain period, the pump may no longer be sustainable to use and require suitable upgrade. In this study, a sustainability review has been conducted on a 250 mm inlet pump that was original selected during the plant design and how it is performing five years later.

Upon comparing the data, the electricity emissions have increased by 46 per cent from the original duty, directly proportional to the yearly power consumed. Wear material emissions have also risen due to the pump experiencing greater load and accelerated wear requiring more frequent maintenance and replacing worn parts. This corresponds to a 25 per cent growth in wear material usage and related emissions. Consequently, the transport needs and related emissions also increases by 25 per cent. Hence, upgrading the pump at the right time is crucial, as once optimally selected pump can become unsustainable over the years as duty change.

Figure 4, visually represent the sustainability metrics. The sustainability metrics currently takes information on snapshot basis by considering the efficiency of new impeller and its performance. While this provides a satisfactory result for starters, the analysis can be further refined by incorporating wear aspects through real time monitoring and benchmarking. Therefore, a potential avenue for future study has been identified.

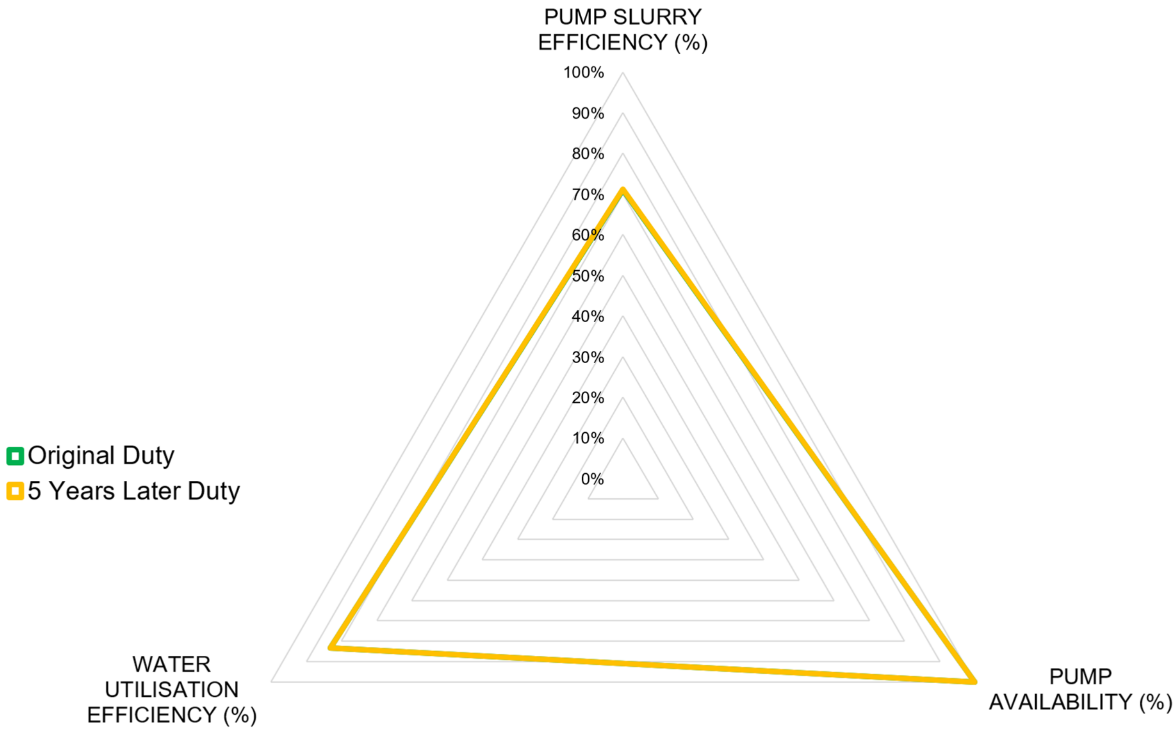


FIG 4 – Sustainability metrics for nickel site pump applications.

Iron ore site – bigger impacts on larger pumps

Sustainability impact on larger pumps, particularly mill discharge pumps, pose a unique challenge due to their sheer size (including higher mass wear components), power requirements to handle higher capacities, the abrasive application and demand for continuous performance. In this case, a 550 mm inlet mill discharge pump operating at an iron ore mine has been selected for the review. Despite higher efficiency, this single pump generates over 4388 tons of carbon dioxide per annum from electricity emissions alone. Wear material emissions and associated transport contribute 18 949.55 kg and 798.95 kg of carbon dioxide per annum, respectively.

Balancing the sustainability and availability of the pumps to meet the production requirements is a key challenge in this application. Mill discharge pumps can be of larger size and have inlet diameters up to 900 mm (Metso Outotec, 2022; Weir Minerals, 2016) or in even exceeding them (KSB, 2022). Additionally, many operations employing large mill discharge pumps tend to have 'duty-only' installations, which means there is no backup standby pump readily available. Hence, directly impacts pump availability. Figure 5 shows sustainability metrics, highlighting a pump availability of 97 per cent, a slurry efficiency of 79 per cent, and a water utilisation efficiency of 90 per cent. Integrating the sustainability metrics with PCMS will help manage not only the sustainability aspects but also availability and overall performance of the pump. Ultimately, resulting to better and more optimal operation of the plant.

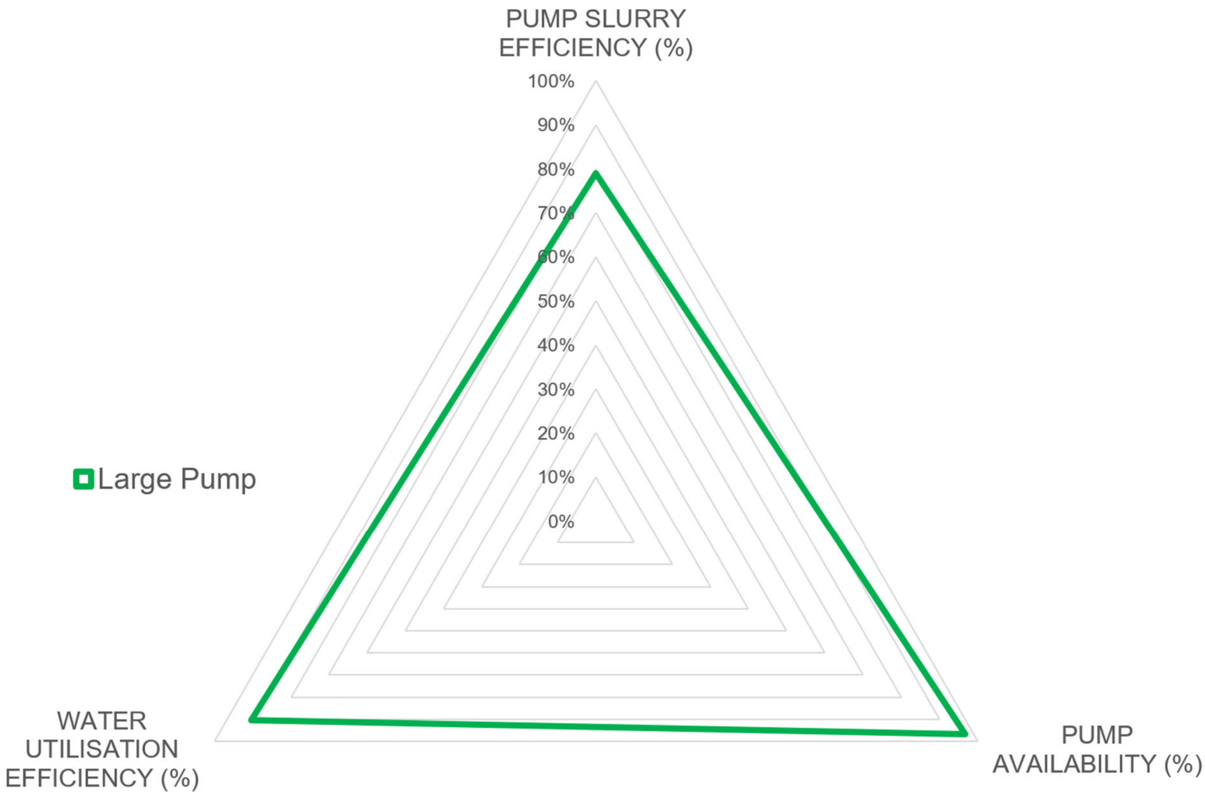


FIG 5 – Sustainability metrics for iron ore site pump application.

CONCLUSION AND FUTURE WORK

This paper highlights the critical role pumps play in the mining industry's pursuit of sustainability. Building on author's previous research, it provides a powerful tool for mining operations to assess and improve sustainability of their slurry pumps. The tool includes methodologies for calculation on CO_2 emissions and sealing water usage. Digitalisation has been recognised as an enabler to sustainability through PCMS and sustainability metrics that allow for tracking and optimisation. Case studies from Iron ore, copper and nickel operations showcased the significant potential for improvement. The findings reveal critical areas for advancement, including choosing the right pump, timely upgrades, and meticulous maintenance, particularly for larger pumps. These insights unveil limitations in current operational and maintenance practices, highlighting substantial benefits achievable through simple monitoring and tracking. Looking ahead, the research acknowledges that PCMS is very much in its infancy in the slurry pump industry and the current level of low cost and reliable wireless sensors is restrictive in which of the developed metrics can be measured in real time. The broadening of the available offering with respect to these sensors will enable a more comprehensive PCMS system that will allow a full sustainability picture to be developed in real time. This real-time data will be a key factor in establishing tangible reduction targets and tracking progress towards a more sustainable future for the mining industry.

ACKNOWLEDGEMENTS

The authors are grateful for the support from many individuals and organisations who have contributed to this research. In particular, Metso and the University of Western Australia for their collaboration. The Planet Positive team and the digital organisation within Metso have made significant contributions to the pumping sustainably initiative. Additionally, the support from global pumps sales and service team at Metso is greatly appreciated.

REFERENCES

Barnewold, L and Lottermoser, B G, 2020. Identification of digital technologies and digitalisation trends in the mining industry, *International Journal of Mining Science and Technology*, 30(6):747–757. https://doi.org/10.1016/j.ijmst.2020.07.003

Ecoinvent, 2020. Ecoinvent 3.7 country specific emission factors. Available from: <https://ecoinvent.org/>

KSB, 2022. GIW® MDX – Mill Duty Extra Heavy Pumps for Severe Mill Duty Applications. Available from: <https://campaign.ksb.com/hubfs/2021%20GM-MDX%204pg%20brochure%20RB_no%20crop-v1.pdf?hsCtaTracking=e29fac9a-f4af-46c5–99e5–3b8807d92e31%7C004fff54–2d18–4fcc-b015–150d5f71a430>

Metso Outotec, 2022. Metso Outotec introduces MDM900, one of the world's largest mill discharge slurry pumps. Available from: <https://www.metso.com/corporate/media/news/2022/1/metso-outotec-introduces-mdm900-one-of-the-worlds-largest-mill-discharge-slurry-pumps/>

Varghese, A, Martins, S, Lessing, E, Hassan, G M and Karrech, A, 2022. Pumping sustainably – power and water consumption in mineral processing plants: someone should care, in *Proceedings of IMPC Asia Pacific 2022*, pp 1506–1527 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Varghese, A, Martins, S, Lessing, E, Hassan, G M and Karrech, A, 2023. Slurry pump safety considerations in mineral processing plants, in Proceedings of MetPlant 2023.

Weir Minerals, 2016. Mill Circuit Duty Pumps, WARMAN® Centrifugal Slurry Pumps. Available from: <https://www.global.weir/globalassets/resources/product-pdfs/warman/warman-mc-mill-circuit-duty-brochure.pdf>

Social responsibility solutions provided by WebGen™ wireless initiation system in open cut mines

W Vilas Boas[1], L Steffen[2], G Stevenson[3], C Braga[4], G Gontijo[5], L Muñoz[6], R Macedo[7] and D Machado[8]

1. Technical Services Engineer, Orica Brazil, 30.390–070, Brazil. Email: washington.vilasboas@orica.com
2. Drill and Blast Manager, Kinross Paracatu, 30.390–070, Brazil. Email: lucas.reis@kinross.com
3. Manager Global Surface Mining – WebGen IPT, Orica Global, Country. Email: geoff.stevenson@orica.com
4. Manager – Technical Services, Orica Brazil, 30.390–070, Brazil. Email: carine.braga@orica.com
5. Lead – Technical Services, Orica Brazil, 30.390–070, Brazil. Email: grazielle.gontijo@orica.com
6. Engineer, Technical Services, Orica Brazil, 30.390–070, Brazil. Email: leopoldo.munoz@orica.com
7. Engineer – Blasting, Orica Brazil, 30.390–070, Brazil. Email: rayla.macedo@orica.com
8. Territory Manager, Orica Brazil, 30.390–070, Brazil. Email: daltro.machado@orica.com

ABSTRACT

Mines operating close to communities face growing challenges, especially with their drilling and blasting activities. Proper management of environmental and community impacts is critical to provide sustainability to the mining business in the long-term, by enabling the licensee to operate. This paper will present new technology solutions to minimise the impacts to communities and the environment from blasting operations. A case study of the wireless initiation projects conducted at Kinross Morro do Ouro Mine (located in Paracatu, Minas Gerais – Brazil), will be presented.

Focused on overcoming the complex challenges in the mine, Orica and Kinross searched for initiatives to optimise the drilling and blasting operations. The team evaluated the *WebGen™* wireless initiation system for controlling environmental impacts as well as operational flexibility and productivity. Since January 2023, three planned wireless blasts to demonstrate the technology and applications were executed. In the tests, the vibration level was able to be maintained lower than the limit of 3.0 mm/s while dust and flyrock impacts were well controlled.

The main benefits of using this technology for the Morro do Ouro Mine are: reducing the number of blasts while increasing the blasted mass per month; control of projection of fragments using additional cover; dust control by watering the bench easily; lightning initiation risk reduction due to the absence of wires or tubes on the surface; flexibility in changing the blast day to better control the noise and dust; flexibility in mine planning mining (potential application in the future).

The use of the WebGen™ wireless initiation system, enables improved productivity while enhancing safety and reducing impacts to communities. Implementation of this technology has enabled Kinross Morro do Ouro Mine to build trust with its neighbours, maintain the license to operate, and helping to mobilise resources in a sustainable way. This has allowed Kinross to position Morro do Ouro Mine as a world reference operation, especially in relation to innovation, safety, and social responsibility.

INTRODUCTION

The Kinross Morro do Ouro Mine is located in Paracatu, Brasil, in the north-west of the state of Minas Gerais. It is the largest opencast gold mine in the country and accounts for approximately 22 per cent of the national gold production.

The mine has unique constraints that demand excellence in operational execution and strict environmental control. These constraints largely arise from the close proximity to the local community and include vibration, noise, fumes, flyrock, dust and the security of explosives. Orica and Kinross know that the success of Paracatu depends on a relationship that respects the surrounding community and the environment. There is a constant need to implement technological innovations and optimise the mining operations to overcome challenges, without neglecting the strict environmental standards adopted by Kinross.

SITUATION

The mine is significantly constrained by proximity to the community, with houses within 500 m of the pit. It also has a relatively low average gold grade of only 0.4 grams per tonne (Kinross, 2023).

The proximity of the community demands control of vibration, dust, noise, flyrock and fumes from blasting. Kinross self-imposes a vibration limit of 3 mm/s (80 per cent less than the Brazilian standard NBR-ABNT9653–2018 of 15 mm/s) and a noise limit of 128 dB, well below the stipulated regulation of 134 dB (ABNT, 2018).

The low gold grade demands control over production costs, high productivity of shovels and mill, and long- term geotechnical stability of the pit walls.

TECHNICAL SOLUTIONS

Focused on overcoming the complex challenges in the mine, Orica and Kinross searched for initiatives to optimise the drilling and blasting operations. The team considered the WebGen™ wireless initiating system for operational flexibility, productivity, and environmental control (Lovitt and Wicks, 2017). The main benefits of using WebGen™ for the Morro do Ouro Mine are listed below.

Reducing the number of blasts while increasing the blasted mass per month

To manage security risks, the operator of Morro do Ouro chooses not to sleep blasts primed with conventional initiation systems. This means the mine must load and fire blasts on the same day. Wireless WebGen™ primers remove this risk (Stevenson, Hassanvand and Adam, 2023), so blasts can be slept. This provides flexibility in planning the number of blasts per month. With conventional systems, the mine has one blasting event per day at 15:20 hrs. Wireless initiation can reduce the number of events from around 20 blasts per month to around eight blasts a month.

Fewer blasting events per month means fewer production stoppages for blasting and less unproductive movement of equipment from the mining face to the exclusion zone, thus reducing costs and increasing production (Stevenson, Hassanvand and Adam, 2023).

Control of flyrock

Due to the proximity of the community and other structures like the processing plant, rock ejection must be controlled when blasting in some sectors of the mine. Measures include blast mats, cover material and long stemming (Muñoz, Vilas Boas and Alarcón, 2024).

With conventional wired and non-electric initiation systems, it is difficult and risky to cover large blasts with fill or mats, because there is a risk the wires or tubes will be entangled in machines or cut (Patterson and Adam, 2023). This creates risk of unplanned initiation and misfires. Mats also limit the size of blasts because there is a limited number of mats.

WebGen™ wireless initiation makes covering a blast much faster, easier, and safer. Machines can safely drive over loaded blastholes to dump fill material and place mats with no risk of causing unplanned initiation or misfires (Muñoz, Vilas Boas and Alarcón, 2024).

The test blasts used 127 mm blastholes with two explosive decks separated by stemming. The decks were fired sequentially to reduce vibration (Cavalcante, 2024). Five metres of stemming and blast matting (Figure 1) was used to control rock ejection, based on an in-depth study using OnBench® and the BlastVison® blast video analysis system (Figure 2).

FIG 1 – Watering and placing mats on a WebGen™ blast.

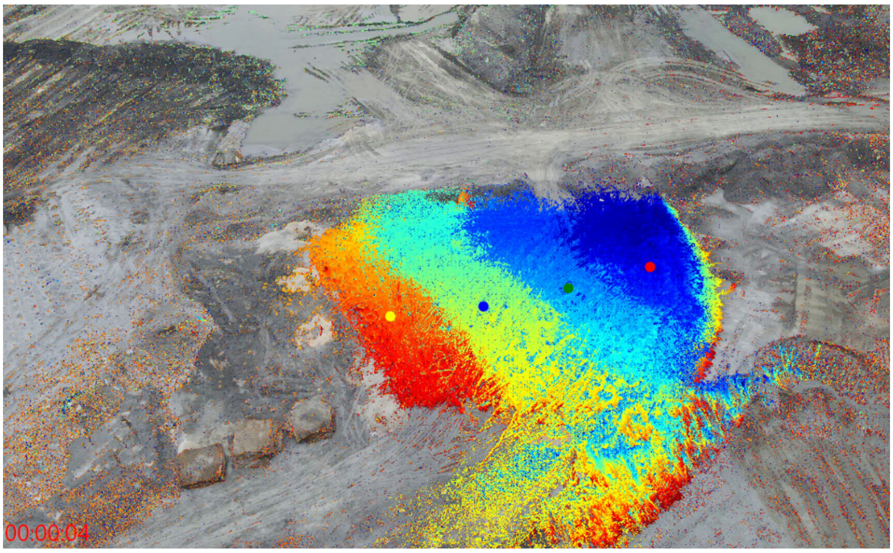


FIG 2 – On-Bench® and BlastVision® tracks rock fragments using drone video.

Dust control

Wetting the bench before a blast is a method used to control dust from blasting. With conventional initiation systems, the water must be applied many hours before the blast, before blastholes are loaded (Aravena *et al,* 2015).

WebGen™ makes this method far more effective. As there are no wires on the surface, the water truck can wet the blast much later in the day (Vilas Boas, Muñoz and Steffen, 2024). The tankers can drive over the loaded blastholes without risk of interaction with explosives. The surface was wet using a water truck around two hrs before the blast, as blast mats were being placed (Figure 3).

FIG 3 – Truck spraying water on the loaded blast pattern.

Lightning risk reduction

Lightning strikes can initiate blastholes primed with conventional wired and non-electric initiation systems. These blasts must be evacuated when thunderstorms approach the mine, and this causes production delays (Stevenson, Hassanvand and Adam, 2023).

Owing to the absence of wires or tubes on the surface, there is no credible way for lightning to initiate blastholes primed only with WebGen™ (Stevenson, Hassanvand and Adam, 2023).

This advantage significantly increases safety and may prevent the need to evacuate and stop production while weather patterns in the area present a risk of lightning occurring. Fewer delays reduces costs by avoiding extra movements, and by increasing production.

Flexibility in changing the blast day to control the noise and dust or unforeseen operational events

The blasting time at the Morro do Ouro Mine is fixed at 15:20 hrs, but blasts are only fired when the wind is blowing away from the city. This rule is in place to reduce overpressure and dust affecting the community. When the wind direction is not favourable, blasting is put on hold until the right conditions occur.

When blasting with conventional initiation systems, it takes at least a few hours to prepare the blast for firing by connecting the surface initiation system (Orica, 2023). This makes it hard to change the blasting plan at short notice and causes wasted efforts when a blast must be disconnected because the wind is not favourable.

WebGen™ allows a blast to be fired at short notice, because there is no need to connect wiring across blastholes and run out firing cables (Stevenson, Hassanvand and Adam, 2023). By using WebGen™ it is easy to change the blasting plan to suit the wind conditions. If a planned blast cannot be fired, there is no effort required to make the blast pattern safe overnight.

Flexibility in mine planning mining (potential application in the future)

As an innovative technology, WebGen™ can ease scheduling constraints imposed by conventional blasting. One example of a future application is to drill and load two benches, then detonate and excavate them separately (Stevenson, Hassanvand and Adam, 2023). This approach will reduce drilling costs and optimise the mining process. Another example is to transform loaded blast into an access road for mining equipment (Stevenson, Hassanvand and Adam, 2023). The method can be implemented only after thorough risk assessment and change management involving Orica Technical Services.

CONCLUSIONS

Morro do Ouro Mine introduced WebGen™ in January 2023, with three planned wireless blasts to demonstrate the technology and applications. Following successful completion of these trials, WebGen™ is now being used for production blasting.

Initially the goal of the first three blasts was to test the technology. However, the technology was validated by the first blast, and the objective of the other blasts was changed to provide training in preparation for WebGen™ application on a large scale.

In the tests, the vibration level was low and the dust was well controlled. BlastVision® and On-Bench® was used to track fly rock, and there were no projections outside the designated exclusion zone.

ACKNOWLEDGEMENTS

Orica would like to thank the trust shown by Kinross Paracatu to carry out this study. The authors are grateful for all the commitment and support shown by the team of engineers of the Orica Latin America technical services involved in the validation and implementation of the proposals, as well as the technical and operational team of the site, who enabled the successful results to be achieved.

REFERENCES

Associação Brasileira De Normas Técnicas (ABNT), 2018. NBR 9653. Guia para avaliação dos efeitos provocados pelo uso de explosivos nas minerações em áreas urbanas, Norma de Procedimento (Guide for assessing the effects caused by the use of explosives in mining in urban areas, Standard of Procedure), São Paulo.

Cavalcante, M, 2024. Vibration control in open cut mine through pre-loading applying wireless detonators, International Society Of Explosives Engineers.

Aravena, J, Gonzalez, D, Gonzalez, R, Gutiérrez, M, Jeric, S, Muñoz, C, Nuñez, C, Olea, F, 2015. Novel drilling and blasting design for vibration, noise and dust control to communities, Enviromine 2015, Lima.

Kinross, 2023. Paracatu, Kinross World. Available from: <https://kinrossworld.kinross.com/en/location/paracatu/> [Accessed: 15 April 2024].

Lovitt, M and Wicks, B, 2017. A new era of blast initiation systems reducing safety risks, costs and enabling automation, European Federation of Explosives Engineers.

Muñoz, L, Vilas Boas, W and Alarcón, J, 2024. Blasting Near Communities: A review of new techniques and technologies to minimize the impact generated by blasting, International Society Of Explosives Engineers.

Orica, 2023. Safe and Efficient Blasting SEB Course, Environmental Impacts of Blasting.

Patterson, R and Adam, M, 2023. Designing The World's Safest and Most Reliable Wireless Blasting System, in *Proceedings of the 26th World Mining Congress: Resourcing Tomorrow; Creating Value for Society*, p 1790 (CSIRO).

Stevenson, G, Hassanvand, A and Adam, M, 2023. Wireless blasting methods safely accelerate production in surface mines, in *Proceedings of the 26th World Mining Congress: Resourcing Tomorrow; Creating Value for Society*, p 2316 (CSIRO).

Vilas Boas, W, Muñoz, L and Steffen, L, 2024. Dust Control in the Environment Using New Technologies and Blasting Techniques, International Society Of Explosives Engineers.

R&D roadmaps in mining and water management – a design-led approach to driving sustainability and innovation

M Yadav[1], K Clode[2] and S Daykin[3]

1. Consultant, Isle Utilities, Sydney, NSW 2000. Email: meena.yadav@isleutilities.com
2. Asia-Pacific Market Leader – Industry, Isle Utilities, Sydney NSW 2000. Email: karen.clode@isleutilities.com
3. Global Head of Mining, Isle Utilities, Sydney NSW 2000. Email: sean.daykin@isleutilities.com

INTRODUCTION

The mining industry faces numerous challenges related to sustainability and circular economy principles, necessitating strategic approaches to innovation and resource management. As demands for mineral resources continue to rise, mining companies are under increasing pressure to address environmental impacts, minimise waste generation, and optimise resource utilisation. These challenges underscore the importance of Research and Development (R&D) roadmaps as strategic tools for guiding innovation and sustainability efforts within the sector (Jochen Berbner, 2022).

A design-led methodology offers a structured approach to R&D roadmap development, emphasising stakeholder engagement, collaboration, and alignment with industry objectives. By leveraging design principles, mining companies can ensure that their R&D initiatives are responsive to evolving challenges and opportunities, fostering a culture of innovation and continuous improvement.

Against this backdrop, the project aims to address the pressing challenges associated with sustainability and circular economy in the mining industry. Through the development of R&D roadmaps and the application of a design-led methodology, the project seeks to identify innovative solutions for enhancing resource efficiency, minimising environmental impacts, and promoting sustainable practices within mining operations. This paper highlights the collaborative efforts among Isle, the mining industry, and water utilities, which have yielded tangible benefits. The study demonstrates how the outcomes from the roadmaps outlined below effectively align research with strategic objectives, fostering innovation to address pressing challenges.

METHODOLOGY

The methodology emphasises the use of design thinking principles and techniques to explore and refine opportunities (see Figure 1). It embraces a design-led emphasis on the critical phases of divergence and convergence in the innovation process. The diverging phase encourages 'outside-in' thinking, facilitating workshops with stakeholders to understand the core challenges and generating diverse options. Conversely, the converging phase helps to refine and narrow down to the most appropriate solution. Stakeholder engagement is identified as a pivotal component, involving ideation workshops to harness collective intelligence (Rikke Friis Dam, 2024).

Following this initial phase, a technology horizon scan is conducted, where identified technology solutions are evaluated using a co-designed framework based on client requirements, considering feasibility, viability, and desirability. Solutions are then subject to techno-economic analysis and due diligence is undertaken on solution providers. Finally, comprehensive R&D roadmaps are developed, comprising three horizons: what can be applied now (Horizon 1), what is new (Horizon 2) and what is next (Horizon 3).

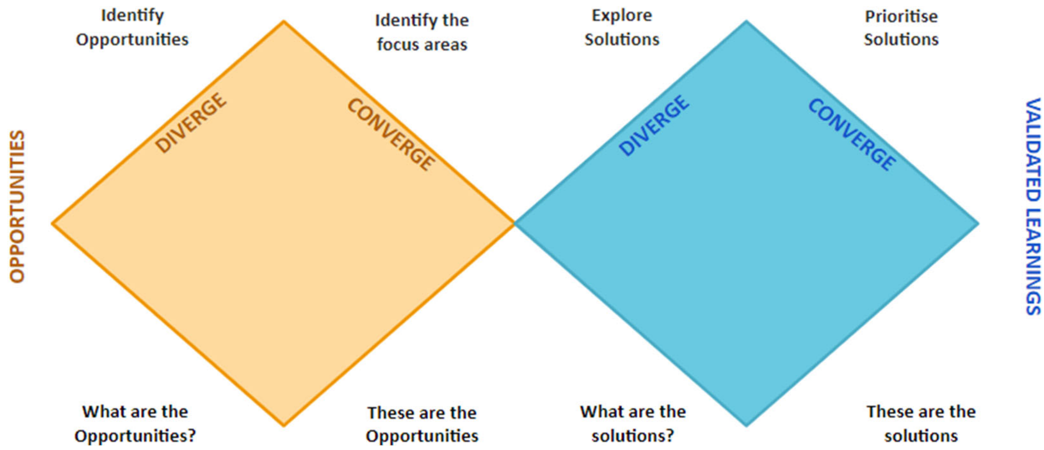


FIG 1 – Methodology – design-led approach.

OUTCOMES FROM CROSS-INDUSTRY R&D ROADMAPS

The following section outlines the outcomes derived from various R&D roadmaps spanning the water industry, mining sector, and government departments. The development of R&D roadmaps in collaboration has yielded significant benefits, aligning research efforts with strategic objectives and fostering innovation to address challenges. These roadmaps have provided a structured framework for guiding decision-making and resource allocation, ultimately leading to improved sustainability and efficiency in these sectors. Isle's actions have yielded several R&D roadmaps for water utilities and mining companies, some of the benefits and roadmaps are as follows:

1. **Mining-influenced water (MIW) remediation and valourisation**: Rio Tinto's MIW roadmap steers the industry towards sustainable mine closure practices. Identifying remediation and valourisation opportunities reduces environmental impacts while recovering valuable resources. To accelerate the identification of MIW R&D opportunities a novel crowdsourcing campaign was launched, which was successful in identifying 15 R&D initiatives with 27 research institutions across the globe, as well as synergistic partnerships. In 2021, Rio Tinto commissioned the Sustainable Minerals Institute at The University of Queensland to undertake a foresight study for MIW treatment technology (Sustainable Minerals Institute, 2021).
2. **Accelerated innovation**: Isle's crowdsourcing campaign accelerates R&D project identification and implementation within the mining sector with respect to water management. This approach fostered collaboration, accelerated innovation through shared knowledge and connected Rio Tinto with organisations that they may not otherwise encounter via traditional means of identifying and sourcing innovation. A two-phase assessment program was followed to ensure that not only was the solution concept robust but there was a diverse range of technology types.
3. **Enhanced resource efficiency**: Water Corporation's 'Circular Economy Integration in Wastewater and Desalination Plants' roadmap, centred on optimising resource use through circular economy principles, holds potential for the mining industry. The outcomes of the roadmap were integrated into the entire life cycle of the treatment plants, encompassing construction, delivery, and operations. Adopting these principles in mining operations could reduce waste, minimise resource consumption, and generate cost savings.
4. **Tailored research initiatives**: The NSW Department of Planning and Environment's 'Research, Technology, and Innovation Roadmap for Water Efficiency' tailors research to regional water efficiency challenges, fostering innovative local solutions.
5. **Strategic direction setting**: 'Gold Coast Water and Waste Business' '3-Year R&D Plan' designed to align research with strategic priorities (City of Gold Coast, 2019), presents a versatile model applicable to the mining sector. The roadmap focused on three key areas – Energy and Carbon, Smart Infrastructure and Waste. Resourcing these key areas is critical for many industries and this roadmap optimises research investments such that they translate into tangible benefits for the business and local communities.

CONCLUSION

The development of R&D roadmaps is transformative across industries. These roadmaps play a pivotal role in addressing complex challenges, driving innovation, and promoting sustainable water management. Isle's design-led methodology, in conjunction with stakeholder engagement and a global network, bolstered by a comprehensive framework encompassing engagement, governance, performance, investment, and delivery, has successfully materialised these roadmaps. The resulting practical roadmaps align research endeavours with strategic objectives, proving advantageous for businesses and communities alike. These well-structured roadmaps adeptly navigate the evolving landscape of the water sector, ensuring its resilience and vitality. They empower organisations to make informed decisions, judiciously allocate resources, and drive innovation, ultimately benefiting their operations and the broader communities they serve. Through collaborative efforts and tailored initiatives, these roadmaps pave the way for achieving long-term sustainability and resilience in the mining sector.

REFERENCES

Jochen Berbner, V L J M, 2022. Navigating a decade of challenges: Five winning initiatives for mining CEOs, McKinsey and Company. Available from: <https://www.mckinsey.com/industries/metals-and-mining/our-insights/navigating-a-decade-of-challenges-five-winning-initiatives-for-mining-ceos>

Rikke Friis Dam, T Y S, 2024. What is Design Thinking and Why Is It So Popular? Interaction Design Foundation. Available from: <https://www.interaction-design.org/literature/article/what-is-design-thinking-and-why-is-it-so-popular>

Sustainable Minerals Institute, 2021. Foresight Study for Treatment of Mine-Influenced Water, The University of Queensland, internal report for Rio Tinto.

City of Gold Coast, 2019. Gold Coast Water Strategy 2019–2024, City of Gold Coast. Available from: <https://www.goldcoast.qld.gov.au/Council/Future-plans-budget/Plans-policies-strategies/Our-strategies/Gold-Coast-Water-Strategy>

AUTHOR INDEX