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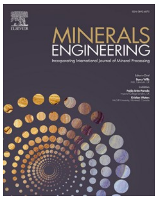

# Integrated and intelligent remote operation centres (I2ROCs): Assessing the human–machine requirements for 21st century mining operations

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ABSTRACT

The futuristic view of smart mines is the attainment of automated self-governed mines without human intervention throughout the value chain. However, reality entails a hybrid environment where humans and machines must effectively work together, with a bias towards machines highly aiding human capabilities. The minerals industry will require systems, processes and strategies to navigate this hybrid environment and transitional period. In this work, we focus on the role that integrated remote operation centres (IROCs) will play in ensuring that mining companies continue to get value from technological advancements during the transformation period. A review of IROC implementations by leading mining companies revealed that most functions in IROCs are powered by low-level artificial intelligence, in which most capabilities are goal-oriented. In this situation, automated machines and processes are programmed to accomplish specific tasks without a two-way intelligent interaction with humans. An integrated and intelligent remote operation centre can provide additional benefits. We refer to such a facility as I2ROC. I2ROCs offer opportunities beyond the traditional command-and-control capabilities by providing analytical insights and the interaction between people and machines, which contributes to better decision-making, ultimately improving performance measurability. In this paper, several enablers of I2ROCs are identified, as well as drivers that will accelerate I2ROCs' attainment. The human element is critical in achieving the 21st Century mining model. As such, this paper takes a two-dimensional approach focusing on the role of humans and technology in the future mining model. Key factors are explored, such as the required skillset and how these skills can be enhanced. Specifically, we present essential elements defining I2ROCs and the critical requirements for a digitalised workforce fit for operation within I2ROCs. Our findings provide a comprehensive framework for multiple stakeholders to collaboratively pursue I2ROCs through effective education, training, and governance, fostering a more sustainable and resilient future.

## 1. Introduction

The adoption of advanced digital technologies has shown promising potential for alleviating some of the mining industry's burdens (Maroufkhani et al., 2022; Onifade et al., 2023), such as persistent decline in ore grades resulting in the need to mine deeper into the earth's crust to access valuable minerals, and the increasingly substantial distances between mine access sites and mining faces or stopes (Wagner, 2019). Over the past two decades, implementing advanced technologies has led to significant improvements in key performance areas (KPAs) of the sector such as health and safety, profitability, efficiency, inclusivity, sustainability and productivity (Marshall et al., 2016; Young & Rogers, 2019; Jang & Topal, 2020). While the adoption of digital technologies presents several opportunities, it is also a complex process to manage as it affects all sections of an organisation (Kretschmer & Khashabi, 2020). Managing the complexity of the processes in the mining value chain (from the extraction of raw materials to the delivery of products) requires operating models that are flexible yet resilient and effective to achieve targeted results even in varying and uncertain conditions.

The shock from the COVID-19 pandemic, which resulted in low levels of productivity (Agbehadji et al., 2021; Ahadjie et al., 2021) signalled the desperate need for a solution that would withstand similar disruptions in the future. The pandemic shockwave underscored the rewards of running 24/7 mining operations and the importance of the human element in mining operations. As such, the drive towards mining automation and integrated remote operation centres (IROCs) became an

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inevitable campaign across industries like mining, which have several facilities that are geographically separated and heavily rely on the collaboration of human capital. Whereas some leading mine organisations had already implemented IROCs in some of their operations during the COVID-19 pandemic (Duff et al., 2010), the reality is that many other mining entities only had traditional command and control centres which focus on section specific activities. Thus, communication and inter-functional tasks could not be achieved across different facilities, resulting in halted operations in most mines.

Unlike, traditional command and control centres whose capabilities and activities are section specific, IROCs are a concept of aggregating information from several geographically separated facilities into a single nerve centre that enables the operation or management of several elements existing at the different facilities (Farelly & Records, 2007). IROCs also allow structured direct communication between production staff and line managers. In addition, IROCs fosters collaboration between information technology (IT) and operations technology (OT), which has always been a challenge in the mining sector (Young & Rogers, 2019) and provides real-time analytical insights that enable smarter decision-making. Consequently, the successful implementation of IROCs requires establishing effective and reliable connectivity across various sensors, devices, machines, and personnel, regardless of environmental conditions and location. It should be noted that the infrastructure currently used in traditional control rooms can be repurposed and integrated to a modern IROC as the systems are similar for most functions, except that IROCs offer a full suite of collaboration across functions.

Enabled by the opportunities of the fourth industrial revolution (4IR), an increasing number of mining companies began to embrace the strategy of IROCs implementation and automation that Rio Tinto, a leading global mining group, had initially demonstrated and implemented at its Pilbara iron ore operations in 2008 and in Perth in June 2010, respectively (Jang & Topal, 2020). The urgency to adopt IROCs has significantly intensified, primarily driven by the COVID-19 pandemic, coinciding with the initial digitalisation strategy stages for many mining companies. While some mining companies, referred to as "digital followers," were just beginning to formulate their digitalisation plans during this period, others faced the challenge of bridging the modernisation divide, particularly among mines of diverse operational maturity and commodities. This divide necessitated retrofitting solutions for older mines, while new mines could readily embrace new technologies. Following the implementation of IROCs, mining companies have reported significant improvement in some of their primary KPAs, which include but not limited to health and safety, profitability, efficiency, inclusivity, sustainability and productivity (Marshall et al., 2016; Jang & Topal, 2020).

Nevertheless, to a greater extent, mining companies use IROCs for operating remote-controlled machines, managing and controlling automated plant systems, as well as pre-and post-processed ore logistics, whereas the value that operations could attain in terms of analytics and new insights has not been effectively harnessed. Some major mining processes that have been automated in most mines include but are not limited to drilling, blasting, excavation, hauling, crushing and milling (Dunn et al., 2015; Ghodrati et al., 2015; Gustafson et al., 2013; Jämsä-Jounela, 2001). To enhance the benefits derived from existing IROCs, we propose an improvement in the level of intelligence currently being used. Hence, we convert ordinary IROCs to integrated and intelligent remote operation centres (I2ROCs). It has been widely argued that the 4IR concept on which digital transformation strategies in the mining industry have been developed, focus on interconnecting and integrating technologies and smart devices to create value (Xu et al., 2021). Unfortunately, the sole focus on using technology to address the industry's challenges creates a gap in the development of human skills required for a digital workplace (Xu et al., 2021).

To this end, the primary aim of this paper is to provide a comprehensive perspective on human-centric integrated and intelligent ROCs, explaining their potential benefits and critical elements. We emphasise the role of humans in achieving connected mines through the I2ROC. Thus, key factors to consider ensuring an adequately skilled human workforce are provided. Ultimately, we propose an approach for planning and implementing I2ROCs that enhance the performance metrics of 21st century mining operations without leaving the human aspect lagging in terms of knowledge, skills and capabilities. To fulfil this aim, we conduct a thorough analysis of case studies within the mining industry, examining the implemented IROCs and evaluating the requirements for their transformation into I2ROCs. We also present projections concerning the important considerations for achieving I2ROCs.

The rest of the paper is organised as follows: In Section 2, a brief overview of opportunities, challenges and achievements of digital transformation in the mining industry, is presented. In Section 3, we focus on the 21st Century mining model, what it constitutes, its drivers and enablers. In addition, we review some case studies of modernisation in terms of the implemented IROCs. Section 4 is dedicated to the proposed I2ROC framework, where its constitution and the required infrastructure are comprehensively provided. Section 5 is dedicated to detailing the required skill set, training needs and approaches to enable the human workforce of the future. In Section 6, a systematic approach to achieving I2ROCs is presented, and the conclusion of the paper is presented in Section 7.

## 2. Brief overview of opportunities, challenges and achievements of digital transformation in the mining industry

The mining industry is one of the significant contributors to global economic development (Dorin et al., 2014), directly by the supply of its products and indirectly by its dependence on other sectors such as manufacturing, energy and technology. A report by Statista (Statista, 2023) revealed that in 2022, 40 top mining companies had a total revenue of approximately 943 billion United States dollars (US$943bn). Despite mining being pivotal to the world's economy, it is currently confronted with a multitude of challenges that impede its operations. These challenges include the persistent decline in ore grades, the need to mine deeper into the earth's crust to access valuable minerals which compromises the safety of miners as the distances between mine access sites and mining faces or stopes, continues to substantially increase (Wagner, 2019). The mining industry also faces mounting pressure to minimise its environmental impact arising from greenhouse gases (GHG) emissions (Irarrázabal, 2006). According to Delevingne et al., (2020) in an article released by McKinsey a business consulting group, mining was responsible for 4 to 7 % of GHG emissions globally, where emissions incurred through mining operations and power consumption, amounted to 1 percent, and fugitive-methane emissions from coal mining were estimated between 3 and 6 %. In addition, the extensive energy requirements and the use of greenhouse emission material of the mining sector (Carvalho, 2017), are classified as indirect mining contributors of GHG emission (Irarrázabal, 2006; Liu et al., 2021). For instance, the energy sector alone is responsible for over 72 % of global carbon emissions (Ritchie et al., 2020). Although it is difficult to precisely quantify how much of this percentage is attributed to mining, Liu et al., (2021) reported that a significant amount of the GHGs are released due to the consumption of energy produced by fossil fuel combustion during mining and mineral processing. The 2020 McKinsey report (Delevingne et al., 2020) estimated the indirect emissions at 28 %. All these challenges negatively impact the industry's performance in terms of health and safety, productivity, cost, operation efficiency, as well as environmental, social and governance (ESG).

Several mining operations have developed digital transformation strategies to address and mitigate the effects of these challenges. This section gives an overview of opportunities, challenges and some of the achievements recorded in the sector.

### 2.1. Opportunities of digital transformation in the mining industry

As technology continues to evolve and flourish, numerous industries have embraced its potential, and the minerals sector is no exception. The advent of the 4IR has opened up a plethora of opportunities for the mining industry (W. Chen & Wang, 2021; Chipangamate et al., 2023; Javaid et al., 2022; Mazibuko & Kraemer-Mbula, 2021; Mishra et al., 2014; Nwaila, Manzi, et al., 2022; Nwaila, Zhang, et al., 2022; PwC, 2021; Young & Rogers, 2019). These opportunities include, but are not limited to:

- Increased utilisation of artificial intelligence (AI) techniques, remote-operated machines, remote monitoring systems, and automation technologies reduce the exposure of workers to hazardous environments, leading to enhanced safety conditions (Mazibuko & Kraemer-Mbula, 2021; Ghasemi et al., 2014).
- Intelligent technologies implemented in production processes optimise resource utilisation, reduce downtime, and streamline operations, resulting in improved overall efficiency (PwC, 2021; Young & Rogers, 2019).
- Sensor networks and data analytics techniques enable rapid identification of valuable minerals, anomalies, and critical infrastructure needs, facilitating faster decision-making and resource allocation (W. Chen & Wang, 2021).
- The availability of vast amounts of data, coupled with predictive and prescriptive models, empowers decision-makers to make informed choices that consider potential risks and optimise outcomes (Nwaila, Zhang, et al., 2022).
- Through leveraging predicted market trends and supply chain insights, mining operations can dynamically adjust their production controls to align with demand, thereby maximising profitability and minimising waste (Bravo et al., 2014).
- Advanced technologies enable remote monitoring of the mining value chain, including exploration, extraction, processing, and transportation, ensuring transparency, efficiency, and oversight across all stages of the operation (Shimaponda-Nawa et al., 2023).
- Utilising technologies such as RFID (Radio-Frequency Identification) and GPS (Global Positioning System) allows for real-time tracking of mining assets, equipment, and personnel, enhancing logistics management and asset utilisation (Mishra et al., 2014).
- Advanced technologies facilitate the adoption of sustainable mining practices, such as precision mining and optimised resource extraction, minimising the industry's environmental footprint and promoting responsible resource management (Javaid et al., 2022).
- Technological advancements enable better characterisation and understanding of ore deposits, improving the efficiency of mineral extraction and enabling the recovery of previously inaccessible or overlooked resources (Nwaila, Manzi, et al., 2022).
- Through the integration of technology, mining companies can enhance communication and collaboration with local communities, regulatory bodies, and other stakeholders, fostering trust, transparency, and sustainable development (Chipangamate et al., 2023).

### 2.2. Challenges of digital transformation in the mining industry

The integration of advanced technologies in the mining industry brings forth significant improvements in various aspects, including health and safety, operational efficiency, data-driven decision-making, and environmental sustainability (Gustafson et al., 2013). These advancements have the potential to revolutionize mining operations and pave the way for a more sustainable and productive future. However, alongside these benefits, the mining sector also faces certain challenges stemming from the rapid advancement of technology. One of the challenges is the shortage of digitally skilled personnel. The successful implementation and utilisation of advanced technologies in mining operations require a workforce that is proficient in digital skills and can effectively leverage these technologies (Ediriweera & Wiewiora, 2021; Lööw et al., 2019). The scarcity of such skilled personnel poses a barrier to the widespread adoption of technology within the sector (Jang & Topal, 2020). Another challenge lies in the cultural and organisational aspects of the mining industry. Legacy culture issues and resistance to change can impede the swift adoption of technology (Clausen & Sörensen, 2022). The entrenched practices and attitudes within mining companies may hinder the integration of advanced technologies, leading to delays in implementation and missed opportunities for improvement.

In addition, the cost and risk associated with investments in digital solutions pose challenges to mining operations. Deploying advanced technologies often requires significant financial investments and entails risks in terms of return on investment (ROI) and operational disruptions (Frolova et al., 2021; Litvinenko, 2020). These challenges are experienced by both new and mature mines, with mine maturity referring to the length of mine operations. For new mining operations, these challenges are relatively manageable in terms of technology adoption, integration of different systems and potential disruptions to operations. However, mature mines face additional complexities. The introduction of modern technology solutions may require retrofitting and integration with legacy infrastructure, leading to potential operation disruptions and difficulties in implementation (Shimaponda-Nawa et al., 2023). The costs of implementing modern technologies in mature mines are also great and may not always match the expected profits. Mature mines also have limited life of mine resources which may not justify the required modernisation. Addressing these challenges will require strategic planning, collaboration between industry stakeholders and technology providers, and investment in reskilling and upskilling the mining workforce. Overcoming these obstacles will be essential to fully harness the benefits and opportunities of advanced technologies fully, enabling the mining industry to embrace digital transformation and navigate the path towards a more efficient, sustainable, and technologically advanced future.

### 2.3. Digital transformation achievements in the mining industry

Although smart mining has experienced exponential growth in the early 21st century (Fisher & Schnittger, 2012), its origins can be traced back to the 20th century, precisely in the 1960 s (Bellamy & Pravica, 2011; Ranjith et al., 2017; Rogers et al., 2019). Significant milestones in the history of autonomous mining were witnessed during this period. One noteworthy advancement occurred in 1967 at the General Blumenthal mine in Germany, where the first unmanned mining rail carriages were deployed (Bellamy & Pravica, 2011). This achievement marked an early foray into automation within the mining industry. Subsequently, in the mid-1970 s, remote-controlled underground machines were introduced, further advancing the automation capabilities in underground mining operations (Rogers et al., 2019; Bonchis et al., 2013). This technology allowed operators to control machinery from a safe distance, improving both efficiency and safety. In the mid-1990 s, remote-operated load and haul machines were introduced for surface mining operations (Bellamy & Pravica, 2011; Marshall et al., 2016). This innovation enabled operators to control and manage the loading and transportation of materials from a remote location, enhancing productivity and minimising risks associated with humans working in hazardous environments. In recent years, smart mining has witnessed continued advancements and innovation. Scholars have investigated and shared several trends in smart mining and the digital transformation advances that the mining industry has undergone over the years (Abdellah et al.,2022; Gustafson, 2011; Marshall et al., 2016). Table 1 presents details of some technological advancements, as provided by various scholars such as Abdellah et al., (2022), Gustafson, (2011), Bonchis et al., (2013) and Marshall et al., (2016) and the referenced work in these articles. Note that the information in Table 1 is presented with what we refer to as a TEP (technology, environment and people) model in mind; where the TEP model refers to a modern approach in

**Table 1**
Innovations relating to digital transformation in the mining industry using the TEP model.

| Applications in Mining | Technological Solution | Operating Environment | Impact on People |
|---|---|---|---|
| Mapping and Surveying | Advanced mobile scanning technologies facilitate both episodic and continuous topographical surveys, significantly enhancing the precision of geological mapping. Robotic maritime vessels are specially designed for bathymetric surveys to chart submarine environments. Vehicle-based high-resolution scanners deliver greater spatial and temporal mapping accuracy. Specialized systems for geospatial drill hole scanning and mapping are also being deployed to obtain detailed subsurface data. | Robotic vessels by Riegl and Trimble are operational for detailed surveys of tailings ponds. Companies like Atlas Copco and Sandvik are known for their advanced spatial mapping technologies. Precision in drill hole mapping is achieved through Leica Geosystems' state-of-the-art equipment. | This leap in technological capabilities streamlines the data acquisition process, ensuring rapid and accurate topographical data collection, thereby substantially reducing the likelihood of human error in manual calibration. |
| Excavation, Loading, and Hauling | Automated Load-Haul-Dump (LHD) machines are multi-functional, handling tasks such as hauling, tramming, and backfilling with high efficiency. The FrontRunner automated haulage system represents a significant leap forward in the autonomous transportation of raw materials. Tele-remote controlled and autonomous dozers have revolutionized earthmoving operations. Additionally, draglines are now equipped with advanced technology for large-scale excavation and landscape modification. | Global manufacturers such as Komatsu, Atlas Copco, Caterpillar, and Sandvik produce these machines, which are in use in diverse mining operations ranging from the Gaby Mine in Chile to the West Angelas Mine in Australia, as well as in the iron ore mines of Western Australia and the diamond mines in Canada. | These advanced technologies necessitate comprehensive operator training to manage the complex machinery. In certain modes of operation, like the line-of-sight remote control, operators may be exposed to safety risks due to the proximity to the equipment. Even in semi-automated operations, continuous oversight is imperative to ensure optimal equipment functionality and to manage resource allocation efficiently. |
| Drilling and Explosives Handling | Autonomous drilling units are now capable of creating precise blastholes, a critical step in the mining process. Sophisticated robotic systems have been developed for the accurate loading and deployment of explosives. Moreover, telerobotic machinery is being utilized to break down ore and rocks remotely, reducing the need for manual size reduction and enhancing safety. | Rio Tinto utilizes these technologies at their Pilbara mine sites in Western Australia. CSIRO's innovative underground solutions have been put to the test at the Cannington Mine in Western Australia, INCO's Research Mine in Sudbury, Canada, and at Rio Tinto Iron Ore's operations. | The implementation of telecommunication and remote operation technologies has markedly improved safety by minimizing the need for human presence in potentially dangerous operational zones. These technological advancements also provide substantial opportunities for professional development and training in high-tech mining operations. |
| Asset and Personnel Tracking, Control, and Monitoring | Radio Frequency Identification (RFID) tags are extensively used for the accurate tracking of equipment, materials, and personnel within complex mining environments. Comprehensive fleet management systems are employed for meticulous position monitoring and production oversight, coupled with task assignments for equipment. Advanced Proximity Awareness and Detection Technologies, along with Collision Avoidance Systems, are incorporated to substantially elevate onsite safety protocols. | RFID systems provided by RF Tags South Africa are implemented in challenging underground mining operations. Examples include the Goldfields, Harmony Gold Mining, and AngloGold Ashanti mines. Caterpillar's collaboration with the Bagdad mine has resulted in the autonomous operation of haul trucks, while Rio Tinto's Remote Operations Centre in collaboration with CSIRO manages operations from over a thousand kilometres away. | The integration of RFID and advanced fleet management systems has significantly enhanced the capability to monitor personnel and assets, ensuring heightened safety, especially in emergency scenarios. While these systems improve situational awareness of potential hazards, they require operator input for control decisions. Such innovations have also led to improvements in worker efficiency, overall quality of life, and provided avenues for the workforce to acquire new and advanced technological skills. |

mining that focuses on technology that is suitable for the mining environment and is people-centric.

The opportunities, challenges, and achievements of digital transformation presented in this section are strong indications of the influence that advanced technologies have on the future of the mining industry. To turn the challenges of digital transformation into opportunities while enhancing the capabilities of the achievements, it is imperative to understand the requirements of future innovations systematically. Thus, the relevance of the current study on I2ROCs. It should be noted that implementing automation and, to some extent, mechanisation of strategies in mining operations is an evolving process instead of a cease and re-establish approach. Therefore, the impact of automation on the economy, jobs, environment, governance, or societal makeup may currently not be succinctly quantified but is expected to be seen over extended periods of time. Most probably, it will involve integration of systems and not replacement of all components. The primary goal remains to improve business insights, move towards low cost and net zero initiatives in terms of health and safety and climate change. In spite of the lack of clarity of the impact of automation and remote operations on the economy, jobs, environment, governance, or societal make-up, IROCs are meant to improve efficiency and efficacy of the system and to enable human–machine interactions, implying that both machine and human enablement are priority.

## 3. The 21st century mine (mine of the future)

Despite the commendable strides made in digitalisation within the mining industry, particularly in the realms of logistics, operations, and sustainability, it is evident that certain mining organisations still face challenges in effectively embracing technological advancements. According to the Digital Acceleration Index (DAI) presented by the Boston Consulting Group, the metals and mining sector lags behind industries such as automotive or chemicals by an estimated 30 % to 40 % in terms of digital maturity (Ganeriwalla et al., 2021). The hurdles associated with digital transformation encompass various factors, including the geographical isolation of many mine operations, which presents difficulties due to inadequate network coverage. Additionally, a shortage of skilled labour and expertise poses further impediments, as does the existence of cultural and ethical concerns regarding privacy (Bhattacharyya & Shah, 2022; Ganeriwalla et al., 2021). A noticeable misalignment between the roles of humans and machines in the context of modernisation is apparent. At present, the mining industry remains predominantly human-driven, with machines functioning solely based on human instructions without autonomous decision-making capabilities. However, the future envisions reduced human intervention in mining operations as technological advancements continue at a rapid pace. While the concept of self-governed mines holds promise, it is imperative to address the current reality of the mining industry before reaching such a stage. In this interim period (i.e., the middle section of Fig. 1), the collaboration between humans and machines becomes pivotal, with machines augmenting human capabilities to a significant extent. Nevertheless, uncertainties remain regarding the timing of achieving fully autonomous mines and the challenges associated with human acceptance, particularly when their financial livelihood is at stake. Given the aforementioned circumstances, this study examines the inevitable transitional period wherein humans and machines work together. Specifically, we direct our attention to the role of ROCs during this transition, aiming to enhance the capabilities of humans in the minerals industry.

The introduction of IROCs in the minerals industry has opened up opportunities for enhancing health and safety, productivity, efficiency, and overall mining sustainability (Batterham, 2014). IROCs leverage data, seamless connectivity, advanced analytics, and cutting-edge technologies such as AI, machine learning (ML), and the Industrial Internet of Things (IIoT). During the transitional period, there is potential to unlock additional value from IROCs by enhancing the intelligence level of machines, thereby further improving their collaboration with humans.

Kaplan & Haenlein (2019) define AI as, a system's ability to interpret external data correctly, to learn from such data, and to use those learnings to achieve specific goals and tasks through flexible adaptation. From this definition, it is easy to relate to the three classes that AI is widely split into based on humans competences such as: (a) cognitive intelligence (b) emotional intelligence and (c) social intelligence. Some elements of cognitive intelligence include pattern recognition and systematic thinking, while those of emotional intelligence may include self-awareness, adaptability, self-confidence, emotional and achievement orientation. Social intelligence includes elements such as team work, empathy, inspirational leadership. While cognitive intelligence which is mainly based on pattern recognition to make future decisions has been widely achieved, the achievement of the social and emotional aspects have been challenging as machines cannot experience emotions hence, cannot naturally be sociable. As such, machines are trained to recognise human emotions in order to appropriately relate with humans. It is expected that from the training of emotion recognition, AI capabilities would move to a higher level where the social competence will be realised, in the long ran. Based on the possessed competences, AI can be classified as analytical, human-inspired and humanised (Kaplan & Haenlein, 2019; Haenlein & Kaplan, 2019). These classes are summarised as follows (Kaplan & Haenlein, 2019; Haenlein & Kaplan, 2019; Turing, 2009):

Analytical AI only possesses cognitive competences, representing the widely achieved AI class. In the mining context, prediction of either accidents or asset failure triggering maintenance, as well as automated ore sorting solutions are some examples under this class. In human-inspired AI, the emotional and cognitive elements are combined, where the human emotions are learned and considered in the decision-

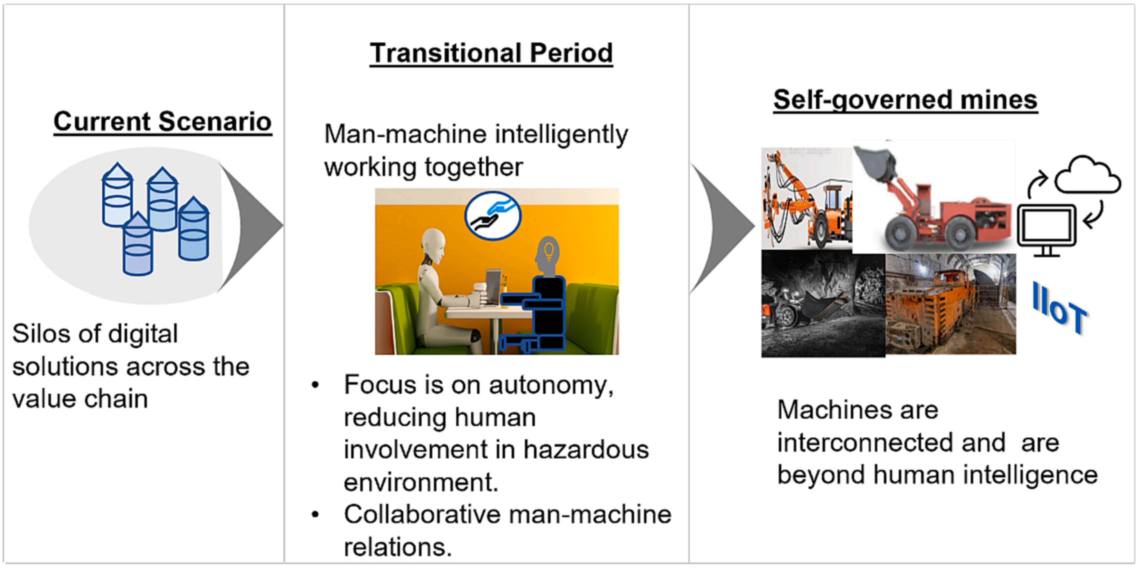

**Fig. 1.** The inevitable transitional period in the progression to future self-governed mines.

making process. Some examples specific to the mining industry include fatigue monitoring systems that asses the emotions of personnel accessing dangerous environments, where access would be denied should the AI enabled system understand and interpret the emotions as unsuitable. On the other hand, the humanised AI is considered as the ultimate intelligence level where all three competences (cognitive, emotional and social) are represented. None of this has been achieved so far. At this level (humanised AI), machines would be expected to be fully self-aware and conscious of their interaction with both their fellow machines and humans. The focus in this paper is the intelligence capability of the analytical and the human-inspired classes.

In relation to the aforementioned classes of AI, three distinct categories that demonstrate the progression levels of intelligence can be created. These progression levels include, artificial narrow intelligence (ANI) relating to Analytical AI, artificial general intelligence (AGI) relating to human-inspired AI, and artificial superintelligence (ASI) relating to humanised AI (Goralski & Tan, 2020; Haenlein & Kaplan, 2019; Turing, 2009). These AI levels represent a progression from machine learning to machine intelligence and, ultimately, machine consciousness as depicted in Fig. 2. While there exists several debates about the definition of consciousness due to its subjectivity as coined by David Chalmers (1995), we submit that at such a level, machines will be aware of their emotions and will also understand that humans have emotions and thoughts that influence how they work and behave. Machines will have an understanding and the capability of processing audio, visual and language in line with human interpretation. As a result, collaboration between humans and machines would be enhanced and humans will benefit by learning certain techniques more efficiently as well as be able to assign difficult/dangerous tasks to machines.

(I) ANI refers to AI systems designed to perform specific tasks within predefined parameters. This is the most prevalent type of AI currently employed across various industries and relates to analytical AI. While machines can even out-perform humans with this level of intelligence, it is still considered weak or narrow because it only operates under specific constraints, that the possessed intelligence cannot to applied elsewhere. For instance, in the case of the mining industry, ANI can be applied to resource evaluation and estimation, which relied on parametric models in the past. This particular model will allow dynamic prediction of in-situ concentration of metals that can be used to cater for the processing plant feedstock requirements. However, the same model will not be applicable for equipment maintenance prediction or for the detection and measurement of toxic gases.

(II) AGI, also known as strong AI, emulates human cognitive and emotional functions such as reasoning, language processing, and image recognition. This type of intelligence would enable machines to apply what they have learned in one area to another area that would not even be familiar. AGI has started to gain traction, especially in the last decade, on operating protocol standardisation within a mine or mining complex and has been applied in fleet management such as directing hoppers to either deliver the ore in stockpiles or directly to the plant, evacuation of mining personnel based on multi-variables that include physical and environmental condition changes.

(III) ASI represents AI with intelligence surpassing that of humans. ASI has not been fully realised in most of the mines, but strides have been made in using blockchain technology for material fingerprinting and assigning digital passports for responsible sourcing of metals. This is still a work in progress but may become more useful in smart mining activities.

In the context of digital solutions used in the mining industry, including IROCs, the prevailing AI type is ANI or weak AI (Bui et al., 2021). These systems operate within the confines of specific instructions and lack the ability to respond effectively to new stimuli or tasks outside their pre-programmed parameters (Haenlein & Kaplan, 2019; Ng & Leung, 2020). While the existing IROCs have already demonstrated numerous benefits, the addition of strong intelligence to the IROC framework holds the potential for further advancements. Current IROC systems may possess learning capabilities based on historical data, but they still lack the ability to adapt to novel situations or go beyond their assigned tasks, which would be achieved at the AGI. Thus, we propose the concept of I2ROCs. I2ROCs offer new possibilities beyond command, control, and monitoring functions, enabling interactions between humans and machines, particularly utilising ML, AI, and the IIoT. Similar to IROCs, data and infrastructure remain crucial components in the I2ROCs concept. However, cognitive and emotional aspects inherent to humans come into play when dealing with I2ROCs, necessitating the development of guidelines to achieve this vision.

To enhance the understanding of the progression of intelligence levels of Fig. 2 in the mining context, we provide specific examples relating to the minerals industry in Table 2.

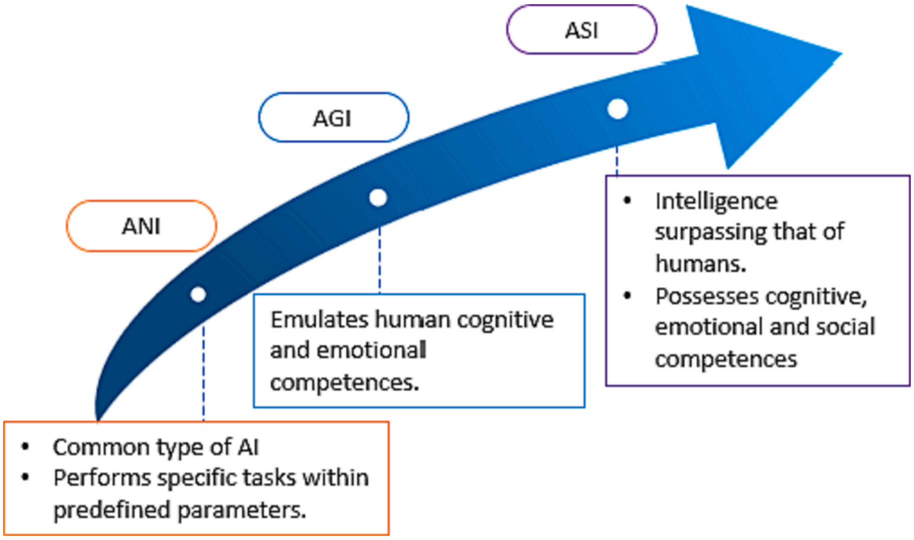

**Fig. 2.** Progression of intelligence levels in terms of cognitive, emotional and social competences.

**Table 2**
Mining examples relating to AI intelligent levels of Fig. 2.

| | Value Chain Step | | | |
|---|---|---|---|---|
| | **Mineral Exploration, Discovery, and Prospecting** | **Planning, Design, and Construction** | **Mining Operations and Extractive Metallurgy** | **Logistics & Markets** |
| **ANI (Artificial Narrow Intelligence)** | Statistical analysis and spatial modeling are employed to assess mineral prospectivity with precision. These methods include geo-statistical techniques, predictive modeling, and GIS-based analysis, offering a robust approach to identifying potential mineral deposits (Yousefi and Carranza, 2015). | Underground mine planning and scheduling are optimized through the use of data-driven decision-making processes. This includes the use of simulation models that replicate various operational scenarios, allowing for strategic planning and resource allocation (Chimunhu et al., 2022). | The evaluation of mineral resources is enhanced by integrating machine learning algorithms, which improve the accuracy and efficiency of processing plant performance. This includes the use of predictive maintenance, process optimization, and quality control (Moraga et al., 2022). | Forecasting models assess the sustainability of cobalt supply, crucial for green energy technologies. These models analyze production trends and market demands to inform policy decisions and strategic resource management (Rachidi et al., 2021). |
| **AGI (Artificial General Intelligence)** | Advanced machine learning models and algorithms are developed for the nuanced prediction and assessment of mineral prospectivity, incorporating complex data sets and predictive analytics to provide comprehensive insights into mineral localization (Parsa and Carranza, 2021). | A multi-stage methodology for long-term open-pit mine production planning is developed, taking into account ore grade uncertainties. This approach utilizes advanced optimization models to improve accuracy in production forecasting and operational efficiency (Jelvez et al., 2023). | Simulation techniques are applied to analyze blending and residence time in mineral processing plants. This helps in optimizing plant layout and operations for enhanced efficiency, throughput, and reduction in operational costs (Estay et al., 2023). | Autonomous haulage systems are implemented to revolutionize mining logistics, enhancing efficiency, cybersecurity measures, and overall safety protocols. These systems are designed to operate in complex mining environments, providing robust logistical support (Gaber et al., 2021). |
| **ASI (Artificial Super Intelligence)** | Cutting-edge adversarial learning techniques are applied to simulate 3-D seismic data, offering unparalleled precision in mineral prospectivity assessment. This involves the use of advanced computational models that can simulate geological processes and mineral deposit formation (Dou et al., 2023). | Deep learning techniques are evaluated for their potential to significantly enhance the simulation of mine production planning and design. This includes the use of neural networks and other advanced AI techniques to improve decision-making processes (Azhari et al., 2023). | Challenges in applying machine learning to optimize mineral processing and extractive metallurgy are addressed, utilizing advanced algorithms to refine processes, increase yield, and reduce environmental impacts (Martins et al., 2020). | Blockchain technology is utilized to ensure traceability and transparency in mineral supply chains. This technology is applied to improve supply chain management, reduce fraud, and enhance the traceability of minerals from the mine to the market (Calvão et al., 2021). |

### 3.1. *Key drivers of a connected mine*

Mining encompasses numerous variables, including people, equipment, systems, the subsurface environment, and various processes within the mining cycle (Domingues et al., 2017). The intricate nature of integrating these different elements, along with the associated hardware and software components, across multiple sections and stages of the mining value chain often leads to the adoption of customised digital solutions. These solutions are tailored to specific sections of a mine or targeted mineral commodities within specific mining operations. While these tailored solutions can enhance performance in their intended functions, they can also create a fragmented landscape of siloed digital solutions, resulting in suboptimal performance when considering the entire value chain. Mining organisations require fully integrated digital solutions to capitalise on the benefits of digitalisation fully. This section identifies and presents key pillars of digitally connected mines, highlighting the importance of integration. Furthermore, it includes selected case studies of IROCs implementation by leading mining companies, serving as compelling examples of connected mines.

A digitally connected mine's key pillars (Fig. 3) are represented with mutualistic emphasis due to their interdependent nature.

a. Sensors and data

Data and information serve as the foundation of a connected mine, constituting valuable assets that drive decision-making processes (Ghorbani et al., 2022). The digitisation of data collected from different stages of the value chain serves a crucial purpose: to establish a unified and reliable data lake accessible across multiple facilities. This transformative process dramatically enhances operational efficiency by ensuring that all decisions are based on a shared and consistent data source. Key components of a connected mine, including infrastructure elements like sensors, sensor networks, cloud computing, edge computing, communication systems, and robust big data analytics platforms, play a pivotal role in achieving this objective. The integration of physical and digital worlds, which underpins the concept of connectivity, heavily relies on using sensors within mining operations (Cacciuttolo et al., 2023). These sensors play a vital role in capturing critical data that both humans and machines utilise for making informed decisions. In a smart mining environment, an extensive network of sensors is strategically deployed throughout the mining infrastructure, including equipment, machinery, and various operational areas. These sensors collect real-time data on a range of parameters, such as temperature, pressure, humidity, vibration, and chemical composition. The accuracy, reliability, and robustness of these sensors are paramount to

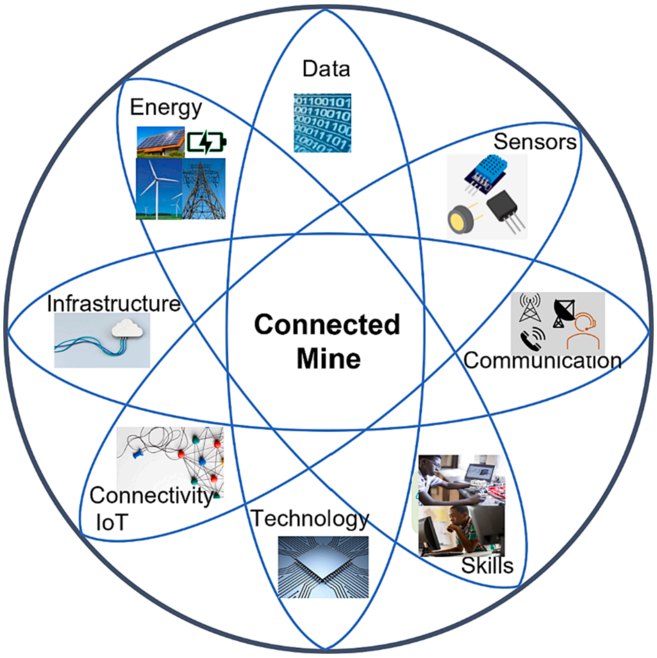

**Fig. 3.** Interdependent drivers of a connected mine.

ensure the quality and integrity of the data being collected. Reliable sensors enable mining companies to monitor and optimise processes, enhance safety measures, detect anomalies, and enable predictive maintenance, contributing to improved operational efficiency and productivity (Mkhabela & Manzi, 2017). The integration of data from sensors facilitates advanced analytics and AI applications in the mining industry. Through the analysis of collected data, mining companies can gain valuable insights into their operations, enabling them to identify areas for improvement, optimise resource allocation, and enhance decision-making processes (Nwaila, Zhang, et al., 2022). Machine learning algorithms can be employed to detect patterns, predict equipment failures, and optimise production schedules. Additionally, data from sensors can be combined with geological and geospatial data to enhance exploration efforts, enabling more precise mineral resource estimation and efficient mine planning (Nwaila, Manzi, et al., 2022).

### b. Technology (IIoT, AI and ML)

The IIoT significantly enables connectivity and data exchange across different mining operations (Boyes et al., 2018). IIoT allows for real-time monitoring, data collection, and analysis by integrating sensors, devices, and equipment. This provides valuable insights into mining assets' performance, condition, and efficiency, helping optimise operations, prevent equipment failures, and enhance safety. AI and ML are changing the mining industry by enabling advanced data analysis and automation (McCoy & Auret, 2019; Pradip et al., 2019). AI algorithms can process and analyse complex datasets to identify patterns, anomalies, and correlations. This enables predictive maintenance, optimisation of production processes, and the discovery of new insights to drive operational improvements. ML algorithms, on the other hand, can learn from data and make accurate predictions or automate repetitive tasks, thereby increasing efficiency and productivity. Moreover, integrating big data analytics with these technologies allows mining companies to unlock valuable insights from the vast amounts of data generated throughout the value chain (Qi, 2020). Through applying advanced analytics techniques, such as data mining, predictive modelling, and optimisation algorithms, mining companies can gain a deeper understanding of their operations, identify areas for improvement, and make data-driven decisions. The impact of these technologies on KPIs in the mining industry is substantial (Hyder et al., 2019). For instance, the implementation of IIoT, cloud computing, and AI/ML has led to significant improvements in health and safety by enabling real-time monitoring of working conditions, early detection of hazards, and enhanced safety protocols (Ghasemi et al., 2014). Operational efficiency has been greatly enhanced through predictive maintenance, optimised resource allocation, and automation of processes (Molaei et al., 2020).

### c. Digital infrastructure (software and hardware)

The aspects of planning and implementation of the digital infrastructure are fundamentals that enable businesses to effectively embrace digitalisation (Ghorbani et al., 2023). Thus, mining companies must have a well-defined strategy and a clear vision regarding the acquisition and management of their digital infrastructure. Cloud computing (Dillon et al., 2010) is another transformative technology that empowers mining companies with scalable and flexible computing resources. According to Sumit Goyal (2013), cloud services are designed to provide easy, scalable access to applications, resources and services. de Moura et al., (2017) notes that one of the means for creating IIoT platforms while reducing the need for high initial investments is adopting cloud computing. By leveraging cloud infrastructure, mining companies can securely store, and process vast amounts of data collected from sensors and other sources. This enables efficient data management, collaboration, and analytics, leading to improved decision-making and operational agility. Thus, the utilisation of cloud services becomes indispensable for mining companies.

In general, the cloud-based digital infrastructure strategies adopted by the mining industry often fall into the category of "as-a-service" models, which include platform as a service (PaaS), software as a service (SaaS) and infrastructure as a service (IaaS) (Rashid & Chaturvedi, 2019). These cloud service models provide mining companies with flexible and scalable solutions, empowering them to handle their data, applications, and computing needs with efficiency. Mining companies can benefit from numerous advantages by leveraging cloud services as part of their digital infrastructure strategy.

PaaS offers a comprehensive platform that enables the development, deployment, and management of mining-specific applications, streamlining processes and enhancing productivity (Keller & Rexford, 2010). SaaS, on the other hand, provides access to specialised software applications hosted in the cloud (Reese, 2009), eliminating the need for companies to invest in costly infrastructure and software licenses. This allows mining companies to focus on their core competencies while leveraging cutting-edge tools tailored to their industry. Additionally, IaaS provides the necessary computational resources, storage, and networking infrastructure on-demand, reducing capital expenditures and providing scalability to meet fluctuating demands (Gibson et al., 2012). It is important to emphasise that the selection and implementation of cloud services should align with the specific requirements and objectives of each mining company. By choosing the appropriate cloud service model, mining companies can optimise their operations, improve data management, and facilitate collaboration across different departments and even over geographically separated facilities. Moreover, the adoption of cloud services paves the way for future advancements in digital technologies, such as AI, ML, and IIoT, allowing mining companies to stay at the forefront of innovation and gain a competitive edge in the industry.

### d. Communication and connectivity

Communication systems serve as the essential backbone of a connected mine, particularly with the increasing focus on remote operations and automation. Moreover, communication systems and technologies are one of the major enablers of digital transformation (Sánchez & Hartlieb, 2020; Vial, 2021). However, due to the nature of the physical mine environment, the performance of most widely employed communication technologies, is affected. Signals of wireless communication systems tend to be affected by several factors such multipath fading, shadowing, scattering, electromagnetic interference and reflection, hence affecting the system's error performance and coverage range. Furthermore, a connected mine will result in huge volumes of generated data traffic. Hence, network performance metrics such as bandwidth, data rates, and throughput become crucial factors to consider. In addition, the successful implementation of various IoT connectivity, including different V2X (Vehicle-to-Everything) technologies, heavily relies on robust and reliable communication technologies. Some of these technologies may require ultra-high speeds and ultra-low latency connectivity, making the quality of service (QoS) configurations for video, voice, and data traffic customisation essential to meet the unique demands of real-time access to these traffic types (Singh & Baranwal, 2018). To ensure seamless connectivity and efficient data transfer, the network within a connected mine must effectively support all types of data. The must accommodate diverse data types, ranging from large datasets generated by sensors and devices to high-resolution video feeds and real-time voice communications. Customisation of QoS configurations becomes crucial to prioritise and optimise the transmission of these data types, taking into account their specific requirements and the criticality of timely delivery. The mining environment poses unique challenges due to its varying conditions. Factors such as rugged terrain, underground operations, and potentially hazardous surroundings can impact the performance and reliability of communication systems (Ferrer-Coll et al., 2012; Seguel et al., 2017). To address these challenges, a hybrid networking approach can be employed, which combines different communication technologies and infrastructures (Shimaponda-Nawa et al., 2022). This allows for a more robust and resilient network that can adapt to the specific conditions and requirements of the mining site. In addition to reliable connectivity, cost-effective access to cloud services is also a significant consideration for mining companies. Leveraging cloud services enables mining companies to efficiently manage their data, access powerful computing resources, and deploy advanced analytics and machine learning algorithms. However, due to the remote nature of mining operations, ensuring cost-effective access to the cloud becomes crucial. Mining companies must carefully evaluate their networking solutions to optimise costs while maintaining reliable and efficient access to cloud services. By prioritising network performance, customising QoS configurations, adopting hybrid networking approaches, and ensuring cost-effective access to cloud services, mining companies can establish a robust communication infrastructure that supports their digital transformation initiatives. This infrastructure enables seamless data transfer, real-time monitoring and control, and efficient decision-making, ultimately enhancing productivity, safety, and operational efficiency in the mining industry (Sánchez & Hartlieb, 2020).

e. Skills for the 21st Century mining model

Mining operations are commonly situated in remote and often challenging environments far from urban centres. Unfortunately, this geographic constraint poses a significant hurdle in attracting a new generation of digital-savvy experts to work in such locations, particularly due to concerns about safety and the perceived lack of appeal (Johansson et al., 2018). Fotta & Bockosh (2000), reported that the average age of mine workers was 45 years old. This average age was projected to increase, highlighting the scarcity of younger talent in the industry. Consequently, there is a pressing need to develop connected mines that enable remote operations, allowing experts to work from their preferred locations while still maintaining productivity. The digital skills required for modern mining operations in the 21st century are pivotal in overcoming these challenges (Young & Rogers, 2019). By embracing digitalisation and connectivity, mining companies can establish remote work environments that leverage advanced technologies to bridge the geographical gap. This expands the pool of potential talent by attracting younger professionals and taps into a broader range of expertise from diverse locations. Connected mines enable experts to remotely access and analyse real-time data, monitor equipment and processes, and collaborate with colleagues across multiple locations. Advanced communication and collaboration tools facilitate seamless interaction and knowledge sharing, fostering a virtual work environment that eliminates the need for experts to be physically present at the mine site. Leveraging technologies such as high-speed internet, video conferencing, virtual, and augmented reality helps experts engage in remote monitoring, troubleshooting, and decision-making processes (Hyder et al., 2019). The ability to work remotely enhances the overall work-life balance for experts in the mining industry. Experts can work from their preferred spaces, whether from home, shared workspaces, or other remote locations, reducing the need for extensive travel or relocation. This flexibility not only attracts younger professionals who value a more balanced lifestyle but also enables mining companies to tap into a global talent pool without the constraints of geographical limitations.

### 3.2. Towards the 21st century mining model: IROC case studies

To illustrate the progress towards the 21st Century mining model, we provide a brief overview of some ROC initiatives that some leading mine organisations have implemented. Based on the information shared by the individual organisations or/and that shared by their contracted partners (see provided website links), we collated and tabulate some of the reported IROC initiatives. Based on our analysis of the shared information about the reported IROC initiatives, Table 3 is framed around

**Table 3**
Selected IROCs case studies.

| | |
|---|---|
| (I) **Anglo Gold Ashanti: Iduapriem Mine in Tarkwa, Ghana** https://im-mining.com/2021/12/10/anglogold-ashanti-ramjack-oioneer-roc-service-target-oee-improvement/ | |
| Brief Facts | • Gold mines<br>Multiple open-pit operation located in western Ghana<br>5.4 million tonnes per annum (Mtpa) |
| ROC Model/ Solution | • ROC as a service offered by RAMJACK a mining technology specialist<br>The ROC is located in Johannesburg, South Africa<br>Initiative is aimed at optimising the performance of the mining fleet, thereby improving the Overall Equipment Effectiveness (OEE)<br>Uses a networked organisation and real-time data generated by the existing Fleet Management System at the mine |
| Impact/ Benefit | Improvements in availability, utilisation and operational efficiency |
| (II) **BHP Group Limited. Western Australia Iron Ore (WAIO); Pilbara, Northern Western Australia.** https://www.youtube.com/watch?v = VPuWp3y0R-s | |
| Brief Facts | • Iron mine<br>Has 5 x Mines, 4 x Processing hubs<br>Mines and processing hubs connected over 1,300 km by rail and port facilities.<br>Every 24 h more than 8,000 truck dumps and 5,700 wagons filled with iron ore<br>Approximately over 280 million metric tonnes of iron ore are moved from pit to port annually |
| ROC Model/ Solution | • Built integrated ROC in 2012 in Perth, within the mine's Integrated Production and Remote Operations (IPRO)<br>Provides real-time monitoring of the mine's network and supply chain<br>Uses remote operated drill rigs to drill operations blast holes where explosives would be loaded.<br>Some sites use autonomous trucks to move ore and waste from the pit to crushers and stockpiles<br>It is basically a fleet management solution |
| Impact/ Benefit | • Increased value across the supply chain<br>Increased operations visibility of end-to-end automated operations<br>Safety of automated fleet management system<br>Better supply chain decisions<br>Process standardisation<br>Poised for increased automation<br>Increased driver health and safety by use of fatigue monitoring through driver eye tracking technology<br>Ergonomically designed workspaces in the ROC facility |
| (III) **Sibanye-Stillwater: Bathopele platinum mine, Rustenburg, South Africa** https://www.canadianminingjournal.com/news/rct-helps-deliver-autonomous-battery-powered-loader-in-africa/ | |
| Brief Facts | • Platinum mine<br>One of the largest platinum reserves in South Africa having estimated reserves of 165 metric tonnes of platinum<br>Produces around 3.7 metric tonnes of platinum/year |
| ROC Model/ Solution | • In 2022, a first in Africa, the mine delivered and operated an autonomous battery-powered loader<br>Assisted by RCT an autonomous solutions specialist Installation of a specialised underground communications network to improve overall connectivity at the mine, enhancing autonomous operations |
| Impact/ Benefit | • Reduction in carbon emissions<br>Remote operations away from mine danger zones |
| (IV) **Gold fields: South Deep, South Africa** https://www.africanmining.co.za/2022/09/01/south-deep-control-through-digitalisation-part1/ | |
| Brief Facts | • Said to be the second largest gold mine in the world, has mineral reserve of just over 1001.5 metric tonnes<br>Massive-mechanised mining operation located in the Witwatersrand Basin, near Westonaria, 50 km south-west of Johannesburg.<br>Built to extract one of the largest known gold deposits in the world.<br>The current Life-of-Mine (LOM) is estimated to be 80 years (2101), thanks to smart mining methods. |
| ROC Model/ Solution | Centralised remote operation centre that allows the mine to manage its people, equipment, and the environment digitally, resulting in safer and smart efficiencies for employees |

(continued on next page)

**Table 3** (*continued*)

| | |
|---|---|
| Impact/ Benefit | • Smart mining enabled, leading to sustainability and increased productivity.<br>Improved safety keeping people from harms' way |
| (V) **Assore Limited & African Rainbow Minerals: Assmang Black Rock Mine Operation, South Africa** https://www.youtube.com/watch?v = qUHxCebtxVQ&ab_channel = JacovanHeerden | |
| Brief Facts | • Contains close to 80 % of the world's Manganese<br>Has 3 underground mining complexes commissioned in 1975, 1981 and 2004 |
| ROC Model/ Solution | • Expansion of the central control room (CCR) that was completed in 2018<br>Now becomes an integrated, centralised, operational control environment.<br>Focused on operations value stream (from mining to product load out)<br>Aims to achieve 24 % improvement in the operations value chain by 2024 |
| Impact/ Benefit | • Plant efficiency, availability and productivity<br>By 2022, productivity improved by 11 %<br>Enabled effective planning based on reliable information |

the following three pertinent questions:

a) What was the proposed solution?
b) What was its impact?
c) Did it benefit people?

Clearly, ROCs are evidence of a connected mine depicting the mine of the future. However, to enhance the capability and value of IROCs, a two-way man–machine intelligent interaction is inevitable.

## 4. The integrated and intelligent ROCs (I2ROCs)

All mines have control rooms used for monitoring critical alarms, alerts and events generated by devices on the network or operators, but not all are equipped with real-time analysis and visual monitoring for the trouble tickets generated by devices or personnel on the network. In addition, some existing control rooms have not yet been equipped with remote control capabilities that enable personnel in the control rooms to take over operations or halt them in case of emergencies. Hence the value of accessing critical information and analytical insights in real-time, such as improved productivity and efficiency while enhancing the health and safety of all mining personnel, has been the driving force behind revolutionising control rooms to IROCs. Using data and advanced analytics enabled by advanced technologies, such as AI, ML and IIoT, several mining giants have implemented IROCs as presented in Section 3.2 (see Table 3). Several ROCs are interlinked for the purpose of having a full view of the value chain and achieving autonomous mining which allows the mine workforce to operate remotely with enhanced safety and productivity, provided the workforce is appropriately trained.

The IROCs cases reviewed in Section 3.2, show that the minerals industry, like most spheres and industries using AI, has currently only achieved the use of narrow AI. This assertion is made based on the current capabilities of the IROCs which are goal oriented such that automated machines and processes are programmed to complete specific tasks. On the other hand, mining operations would benefit more from the use of strong artificial intelligence or human-inspired, where the human–machine relationship is intelligently interactive. As earlier mentioned, we refer to such type of IROCs as Integrated and intelligent ROCs.

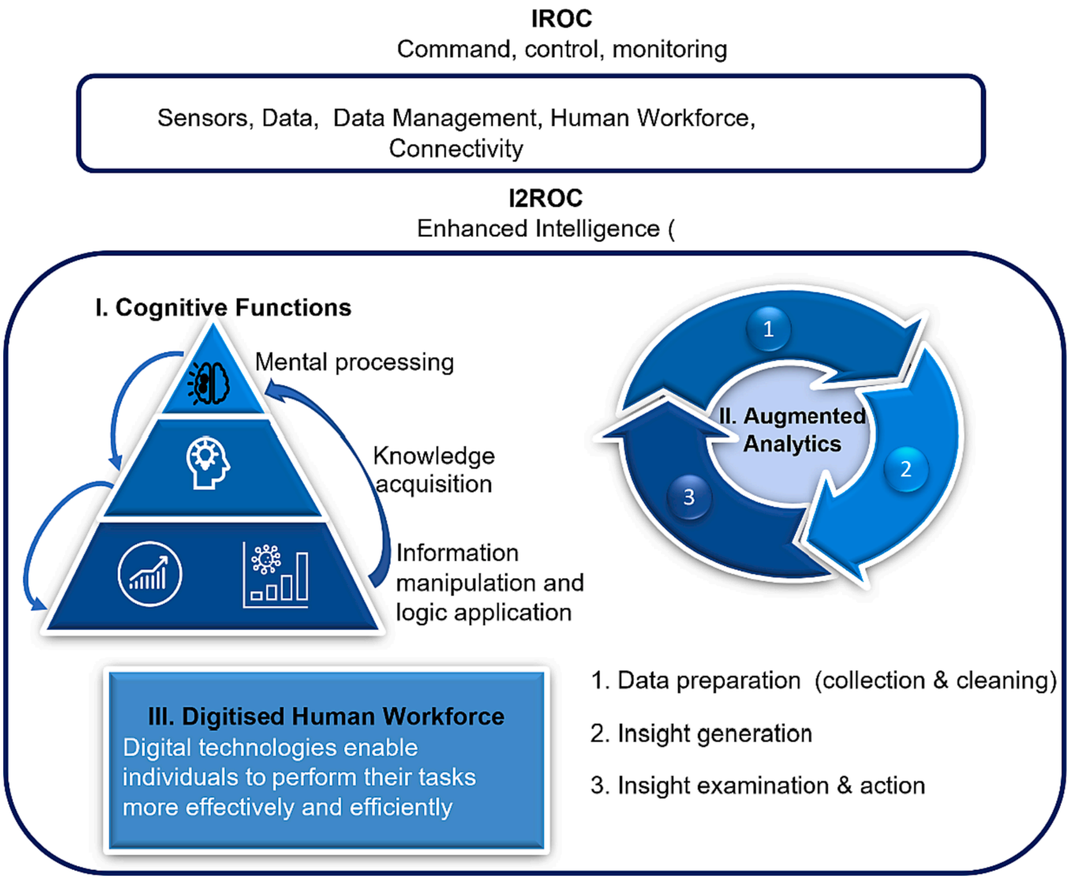

**Fig. 4.** Elements of I2ROCs built on the capabilities of IROCs.

### *4.1. Elements of I2ROCs*

The I2ROCs concept focuses on enhancing the capabilities of machines that must be indistinguishable from human behaviour in terms of audio, visual and language interpretation. In Fig. 4, some key elements constituting I2ROCs are shown. As shown in Figs. 4, I2ROCs are simply an enhancement of IROCs with strong built-in intelligence to enhance the man–machine relationship. As such, all benefits of IROCs are automatically assumed by I2ROCs. In addition to the elements of IROCs indicated in Fig. 4, cognitive functions, augmented analytics, and a digitised human workforce are inevitable to achieving I2ROCs.

(a) Cognitive functions

In the Encyclopaedia of Quality of Life and Well-Being Research, cognitive function is defined as the encompassing term that describes various mental processes involved in acquiring knowledge, manipulating information, and reasoning (Kiely, 2014). Kiely (2014) identifies six distinct domains that contribute to cognitive functions: (a) perception, (b) memory, (c) learning, (d) attention, (e) decision-making, and (f) language abilities. These domains play a crucial role in the collaborative work culture between humans and machines, as they form the foundation for enhancing human–machine interactions within the realm of I2ROCs. Systems and machines equipped with the six domains of cognitive functions identified by Kiely (2014) can interact meaningfully and productively with humans. This interaction is particularly relevant in industries such as mining, where the adoption of I2ROCs can lead to significant improvements in key areas of performance. With enhanced perception, memory, learning, attention, decision-making, and language abilities, mining companies will likely experience advancements in various operations. The utilisation of I2ROCs in mining companies can profoundly impact their overall performance. For instance, improved perception can enhance the ability to accurately detect and identify valuable minerals or potential hazards. Enhanced memory and learning capabilities can facilitate accumulating and retaining important geological information and procedural knowledge. Attentional processes can be sharpened to maintain focus on critical tasks, while improved decision-making can lead to more efficient resource allocation and problem-solving. Additionally, language abilities can be enhanced to facilitate effective communication between humans and machines, enabling seamless collaboration in mining operations.

(b) Augmented analytics

Augmented analytics refers to the utilisation of enabling technologies such as ML and AI to support data preparation, insight generation, and insight explanation (Alghamdi & Al-Baity, 2022; Prat, 2019). Its purpose is to augment how individuals explore and analyse data within analytics and business intelligence platforms. Augmented analytics is of utmost importance as it enhances the human capacity to interact with data while considering their cognitive capabilities and physical and social environments. The future will focus on intelligent collaboration between humans and machines through augmented analytics, resulting in more effective decision-making. This technology enables the discovery of insights that humans may not have been able to uncover otherwise. The significance of augmented analytics lies in its ability to enhance the entire data analysis process. As a result of ML and AI technologies, augmented analytics enables individuals to better understand and navigate complex datasets. Integrating these technologies into analytics and business intelligence platforms provides valuable assistance in tasks such as data preparation, where time-consuming and repetitive tasks can be automated. Augmented analytics facilitates insight generation by leveraging advanced algorithms and statistical models to identify patterns, correlations, and anomalies within the data. The technology enables insight explanation, helping individuals understand and interpret the results obtained, thus supporting informed decision-making. The future of analytics and business intelligence revolves around the collaboration between humans and machines, with augmented analytics playing a pivotal role in this partnership (Alghamdi & Al-Baity, 2022). By combining the unique strengths of humans, such as critical thinking and domain expertise, with the capabilities of ML and AI technologies, augmented analytics expands the possibilities for data exploration and analysis. Through this collaboration, individuals can harness the power of technology to uncover insights that may have remained hidden, leading to more effective decision-making processes and improved business outcomes. Augmented analytics paves the way for a future where humans and machines work together intelligently, leveraging each other's strengths to maximise the value derived from data.

(c) The digitised human workforce in the mining industry

The emergence of digital technologies significantly impacts how jobs are structured and defined, particularly in industries such as the mining industry. This transformation presents opportunities for creating new roles and challenges in meeting the demand for skilled workers to fill these positions. In recent years, digital technologies have substantially influenced various aspects of human life, including job profiles (Pontes et al., 2021). While there is no universally accepted definition of a digital workforce, in the context of human workers, we can define it as using digital technologies to enable individuals to perform their tasks more effectively and efficiently. This is achieved through various means, such as enhancing connectivity between people and infrastructure, providing digital training, and facilitating team integration beyond the traditional office environment. The digitised human workforce in mining is characterised by integrating digital technologies into everyday work practices. These technologies enable workers to transcend physical boundaries and connect with colleagues, resources, and infrastructure more seamlessly and efficiently (Leitao et al., 2020). With enhanced person-to-person and person-to-infrastructure connectivity, mining professionals can collaborate and communicate effectively, regardless of their geographical locations. This connectivity allows for real-time data sharing, remote monitoring, and instant access to information, thereby improving decision-making processes and overall operational efficiency. Digital technologies facilitate the digital training and upskilling of mining personnel. Through online learning platforms, virtual simulations, and augmented reality tools, workers can acquire new skills, enhance their knowledge, and adapt to evolving industry requirements. This digital training approach allows for flexible learning experiences that can be accessed anytime and anywhere, reducing the limitations imposed by traditional classroom-based training. Moreover, digital technologies enable the integration of multidisciplinary teams beyond the confines of the physical office space. Remote collaboration tools, cloud-based platforms, and virtual workspaces empower individuals to collaborate, share expertise, and contribute to projects regardless of location.

### *4.2. Required infrastructure*

ROCs and I2ROCs can be categorised as forms of dry laboratories. The concept of a dry laboratory, as defined by Ghorbani et al. (2023), refers to a laboratory primarily focused on the utilisation and creation of data. In their research, Ghorbani et al. (2023) specifically investigated the instrumentation and infrastructure necessary for real-time monitoring, analysis, and characterisation within the minerals industry. They discovered that while different tools and equipment may be utilised at different stages of the mineral value chain, data management and infrastructure requirements remain similar. Ghorbani et al. (2023), as well as other scholars (Kolade & Cheng, 2022; Li et al., 2015) highlight the importance of infrastructure addressing aspects such as data collection, digitisation techniques, data transmission and management, big data analytics (descriptive, diagnostic, cognitive, prescriptive, and predictive), as well as data visualisation. Since Ghorbani et al. (2023) provide a comprehensive discussion on infrastructure requirements for dry laboratories, this paper does not delve further into this aspect. In addition to the infrastructure requirements shared with dry laboratories, I2ROCs necessitate the utilisation of resources and technologies that enable the achievement of strong or general artificial intelligence. The key objective is to develop machines capable of intelligent interactions with humans, seamlessly blending in without any noticeable distinction. To accomplish this, a digitised human workforce, comprising both the existing workforce and the new talent from the digital generation (younger generation), plays a central role in the realisation of I2ROCs. The integration of a digitised human workforce into I2ROCs is crucial for successful collaboration between humans and machines. It involves leveraging the skills and expertise of both the existing workforce and the technologically proficient younger generation. The digital generation brings fresh perspectives and technological fluency, while the existing workforce offers domain knowledge and experience. This collaborative approach ensures that I2ROCs can effectively harness the capabilities of humans and machines, ultimately leading to improved operational efficiency, decision-making, and overall performance.

## 5. Enabling a digitised mining industry workforce

Infrastructure, while critical, is only an enabler for I2ROCs. Mining organisations stand to get the true benefit of 4IR of efficiency and competitive advantage if an empowered workforce is deployed. The subject of the role of humans in the future of mining has raised a lot of concern and debate, where futuristics predict an era of self-governed mines where humans will only own mines without actively being involved in the operations and decision-making. However, a sustainable mine of the future must be people-centric. Ultimately, the 21st Century mining model enables intelligent two-way communication between humans and machines. Therefore, humans must be rightly trained and inducted using platforms similar to actual working spaces in the real digital mining world (Fig. 5). Some areas of critical consideration revolve around enabling the digital workforce through training for new talent, mostly the younger generation, and reskilling the current workforce. In this section, we highlight fundamental approaches that can be adopted to enable the human workforce in a digitised minerals industry.

### 5.1. *Appropriate training for a digitalised workforce*

1) Transformation acceptance sessions

One of the hurdles digital transformation has faced in the minerals sector is the human workforce's lack of acceptance of digital solutions (Ediriweera & Wiewiora, 2021). Since the I2ROCs concept is enabled by technology, appropriate staff training at various levels of the corporation is crucial. These sessions must show the benefits of the proposed digital solutions and address the perceived dangers and misconceptions. This is with the assumption that these solutions have been developed to be human-centric. Training sessions must also provide the organisation's vision and emphasise that the human workforce is critical to the transformation process. Transparency about the inevitability of new job profiling is key to providing the realities of changes in skills requirements emanating from digital transformation.

2) Simulation-based training

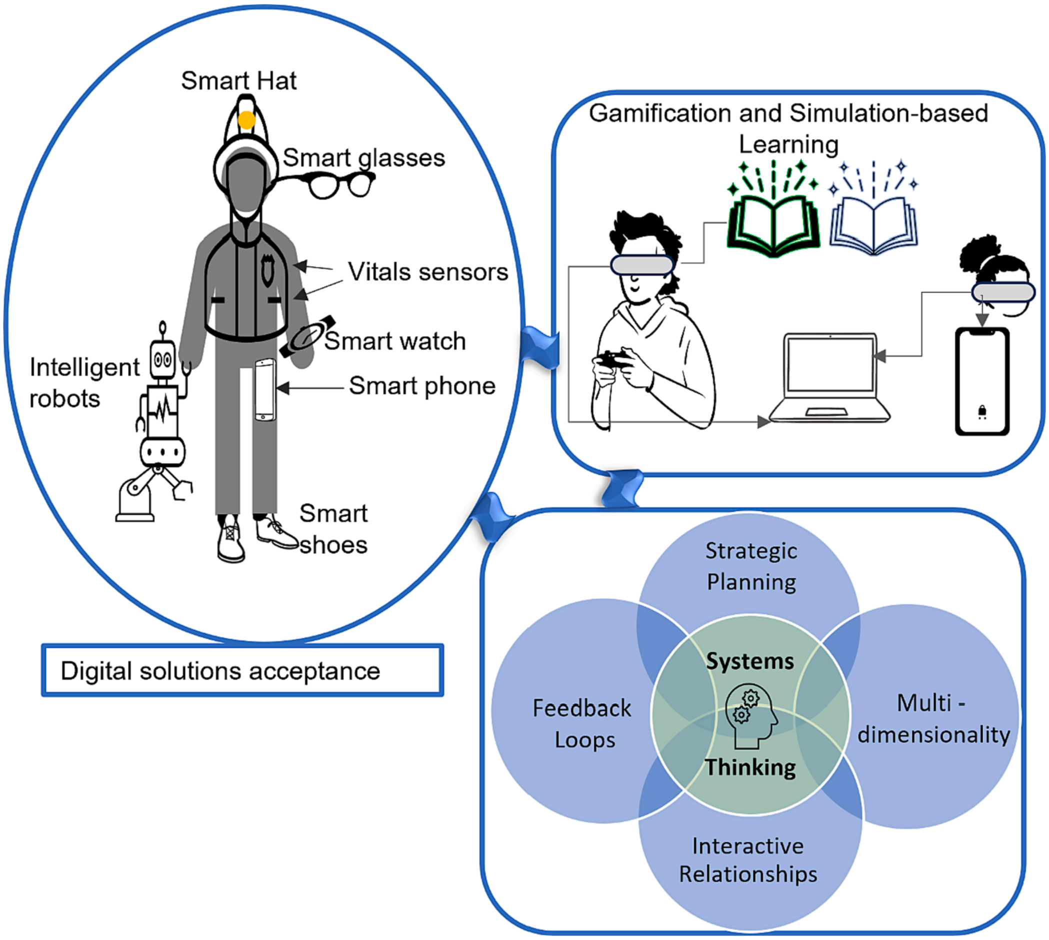

**Fig. 5.** Fundamental training approaches for the digital mine of the future.

Simulation-based training plays a crucial role in preparing integrated teams of stakeholders, from the shop floor to the boardroom, for real-world work environments. This training method involves creating simulated situations that mirror real-life scenarios, allowing personnel to acquire the necessary skills and experience required for their roles (Moorthy et al., 2005). One of the key advantages of simulation-based training is that it provides trainees with a safe environment to make mistakes and learn from them without facing any actual repercussions. Trainees can gain valuable insights into how their actions affect other functions within the value chain by immersing themselves in these simulated scenarios. The use of simulation-based training enables participants to develop practical skills and knowledge in a controlled setting (Z. Chen et al., 2016). Through realistic simulations, individuals can engage in hands-on learning experiences that closely resemble the challenges they may encounter in their actual work environments. This form of training allows participants to practice critical thinking, problem-solving, and decision-making skills within a risk-free context. They can explore different approaches, experiment with strategies, and observe the immediate outcomes of their actions. By simulating real-life situations, simulation-based training prepares individuals to handle complex scenarios and equips them with the ability to respond effectively in high-pressure situations. Simulation-based training promotes collaboration and teamwork among integrated teams of stakeholders. By simulating a holistic work environment that spans from the shop floor to the boardroom, this training method encourages participants to understand and appreciate the interdependencies between various functions within the value chain. Trainees gain insights into how their decisions and actions impact other team members and departments, fostering a sense of collective responsibility and collaboration. Through working together in simulated scenarios, individuals can enhance their communication skills, develop cross-functional understanding, and build effective working relationships across different levels of the organisation.

3) Gamification-based training

Gamification-based training, according to online education specialist Study.com, involves transforming the traditional classroom environment by incorporating gaming themes and elements. Gamification encourages active participation and motivates participants by introducing game-like elements, such as leader boards, badges, and levels (Kapp et al., 2014; Orhan Göksün & Gürsoy, 2019). In the context of the mining industry's 21st century model, attracting a large number of young talents is crucial to bridge the skills gap. Study.com's lesson on "Understanding and Teaching the Digital Generation" emphasises that students in the 21st century are accustomed to interacting with screens, seeking speed, and accessing vast amounts of information. Therefore, it is essential for training programs in the minerals sector to adopt creative and interactive approaches that resonate with learners from the digital generation. Failure to do so may result in the minerals industry failing to align with the future job profiles of mining. Incorporating gamification into training programs can offer several benefits. First, it captures the attention and engagement of learners by leveraging the principles of gaming, such as challenges, rewards, and competition. This approach taps into the digital generation's affinity for interactive and dynamic learning environments, making training more enjoyable and memorable.

Furthermore, gamification-based training fosters a sense of exploration, experimentation, and problem-solving among learners (Kiryakova et al., 2014, 2014; Orhan Göksün & Gürsoy, 2019). Simulations and gamification enable trainees to apply their knowledge and skills to solve challenges and make decisions in a risk-free environment. This enhances their understanding of mining concepts and processes and cultivates critical thinking and decision-making abilities. Gamification can also provide instant feedback on performance, allowing learners to track their progress, identify areas for improvement, and strive for mastery. To align training in the minerals sector with the expectations and preferences of the digital generation, gamification offers a promising approach. The mining industry can attract and retain young talent by embracing interactive and gamified training methods. This approach not only enhances training effectiveness but also contributes to closing the skills gap by equipping learners with the necessary knowledge and skills to meet the demands of future mining job profiles.

4) Systems thinking training in the mining industry

Systems thinking training is essential for personnel across an organisation to develop a holistic understanding of their roles and the larger context in which they operate. Strategic thinking, multidimensionality, interactive, collaborative relationships, and feedback loops play crucial roles when planning and implementing digital transformation strategies. To effectively contribute to these initiatives, all stakeholders must be trained to think holistically, aligning with their respective levels and responsibilities. This training approach helps individuals recognise the criticality of their individual roles within the broader business ecosystem. A better understanding of and appreciation for stakeholders' roles in the value chain can lead to better collaboration and better organisational decisions (Arnold & Wade, 2017; Monat & Gannon, 2015). Systems thinking training encourages a shift from a narrow, siloed mindset to a more comprehensive perspective considering various organisational elements' interdependencies and interconnectedness. It promotes an understanding that individual actions and decisions can have ripple effects throughout the system. When stakeholders view the organisation as a complex system of interrelated parts, they better understand their decisions' potential consequences and impacts. This enables them to identify and leverage opportunities, mitigate risks, and develop more effective strategies. Systems thinking training fosters a culture of collaboration and collective problem-solving. It emphasises the importance of interactive, collaborative relationships, where stakeholders from different functions and levels of the organisation work together towards shared goals. Through this training, individuals learn to appreciate each stakeholder's diverse perspectives and expertise (Anderson & Johnson, 1997; Monat & Gannon, 2015). They recognise that effective collaboration and communication are essential for achieving synergy and optimising the organisation's overall performance. It is easier for organisations to navigate the uncertainty and complexities of the digital transformation journey by instilling systems thinking capabilities in their personnel. This training equips stakeholders with the ability to identify patterns, analyse feedback loops, and understand the underlying dynamics of the system. It encourages proactive thinking, innovation, and adaptability in response to evolving challenges and opportunities.

### *5.2. Reskilling the current workforce*

The rapid emergence of digital solutions across industries, including the mining sector, highlights the need for a workforce that is appropriately empowered and equipped with relevant skills. Numerous studies have emphasised the importance of reskilling and upskilling the current workforce to ensure a smooth integration into the digitally transformed workplaces of the future (Li, 2022). Reskilling and upskilling initiatives are crucial because they enable existing employees to acquire new knowledge, competencies, and capabilities that align with the evolving demands of digital technologies and processes. Mining firms can ensure that their workforce is still relevant and flexible in a world that is becoming increasingly digital by investing in reskilling programmes. This proactive approach allows organisations to leverage the existing talent pool and maximise the potential of their workforce. Reskilling the current workforce involves identifying the skills gaps and future requirements within the mining industry. This assessment serves as a basis for designing comprehensive training programs that address specific areas of development. These programs can encompass various topics, such as data analysis, automation, artificial intelligence, digital literacy, and cybersecurity. Organisations can provide their staff with the knowledge and tools they need to adopt new technologies and successfully participate in efforts to implement digital transformation by doing so. Reskilling initiatives benefit the individual employees and the overall organisational performance. By nurturing a learning culture and investing in continuous professional development, companies can enhance employee engagement, retention, and job satisfaction. Reskilled employees bring fresh perspectives, innovative ideas, and enhanced productivity, driving organisational growth and competitiveness. It is worth noting that reskilling and upskilling efforts should be ongoing and adaptive to keep pace with technological advancements. The digital landscape is continuously evolving, and new technologies emerge regularly. Therefore, mining companies must establish continuous learning and upskilling mechanisms to ensure their workforce is equipped with the latest knowledge and skills.

## 6. Systematic approach to implementing I2ROCs

Implementation of the I2ROCs is a complex process as it requires the participation of several stakeholders and shareholders. Iterative processes through all phases, from conception to implementation, are inevitable. Here, we provide an overview of some areas (Fig. 6) that require consideration during the process of I2ROCs implementation strategies.

### 6.1. *Bridging the gap between IT and mining education*

The mining industry is increasingly moving towards IROCs, highlighting a significant gap between IT education and domain-specific needs which often include operational technology. Institutions must respond by revamping their curricula to offer hybrid programs that blend advanced IT skills, like data analytics and machine learning, with traditional mining education (Karakolis et al., 2022). These revamped curricula are not merely an academic overhaul, but a necessary response to the industry's evolving landscape, which demands a workforce proficient in both IT and mining disciplines. The integration of data analytics and decision support services into mining education aligns with the need for a more technologically agile and innovative workforce (Kontzinos et al., 2019). Moreover, a deep understanding of mining operations, geology, and process optimization needs to be complemented with IT proficiency to truly innovate and optimize in this field (Meng et al., 2023; Cui et al., 2023). It is imperative that educational institutions and industry leaders collaborate closely, ensuring that the curriculum not only stays relevant but also anticipates the future needs of the mining industry (Srivastava et al., 2023).

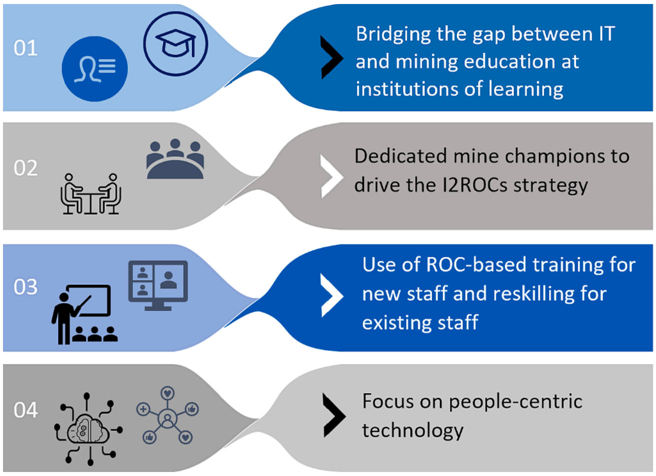

**Fig. 6.** I2ROC implementation considerations.

#### 6.1.1. *Mining industry-academia collaborative models*

The evolution of the mining sector, with its increasing reliance on technology, necessitates a robust collaboration between academia and industry. This partnership is essential for preparing a workforce capable of handling the sector's unique challenges and leveraging its opportunities. Industry-sponsored projects and internships provide students with invaluable exposure to cutting-edge technologies and real-world challenges, bridging the gap between theoretical knowledge and practical application (Saha et al., 2023). Additionally, the infusion of industry expertise into academic settings through guest lectures or joint research initiatives enriches the educational experience and ensures that graduates are well-equipped to meet the demands of the industry (Chen et al., 2023; Dallegrave and Santos, 2023). These collaborative efforts not only enhance the quality of education but also drive innovation, leading to novel solutions that are attuned to the intricate demands of the mining sector.

#### 6.1.2. *Continuous professional development and reskilling in the mining industry*

As the mining industry undergoes rapid digital transformation, the imperative for continuous professional development and reskilling becomes increasingly evident. Professionals within the industry must continually update their skills to keep pace with the latest advancements in IT and digital technologies. This commitment to lifelong learning is vital for harnessing the full potential of technologies such as cloud computing, data analysis, and cybersecurity within the mining context (Sofia et al., 2023). Reskilling initiatives are not just about staying current; they are about pushing the boundaries of what's possible in mining operations, ensuring that the industry as a whole remains competitive and innovative. Tailored training programs focusing on the specific needs of the mining industry can significantly enhance problem-solving and decision-making capabilities, ensuring a seamless integration of new technologies into existing operations (Bester and Uys, 2023; Hearn et al., 2023). By prioritizing continuous learning and skill development, the mining industry can effectively navigate the complexities of digital transformation and maintain its competitive edge.

#### 6.1.3. *Fostering a culture of innovation and multidisciplinary collaboration in the mining industry*

To effectively bridge the gap between IT and mining, it is imperative to foster a culture of innovation and collaboration within the industry. Encouraging students to engage in multidisciplinary projects, where IT and mining expertise converge, prepares them for the collaborative and innovative efforts required in modern mining operations (Strachan et al., 2023). Educational institutions play a crucial role in cultivating this environment by simulating real-world scenarios where diverse teams work together to address complex mining challenges. Furthermore, the industry must embrace a culture that values continuous education and collaboration, promoting innovative spaces like hackathons and labs where professionals from various disciplines can brainstorm and develop new solutions (Zhao et al., 2023; Hearn et al., 2023). This collaborative approach not only enhances the learning experience but also drives the industry forward, producing novel, efficient solutions that leverage the best of both IT and mining expertise. Fostering a culture committed to innovation and teamwork enables the mining industry to navigate and capitalize more effectively on the opportunities presented by digital transformation.

### 6.2. *Dedicated mine champions to drive the I2ROCs strategy (Chief I2ROCs officer)*

The importance of having a dedicated function champion cannot be overstated when it comes to I2ROCs. These concepts are complex and require a senior executive who will focus on leading teams throughout the strategy's planning, organising, executing, and maintaining phases. Individual mining companies and operations have unique requirements for remote operations solutions, influenced by factors such as location, mining types, size, and years of mining operations. Therefore, it is essential to appoint a Chief I2ROCs Officer or a dedicated executive who can lead and spearhead strategies aimed at achieving I2ROCs. The role of a Chief I2ROCs Officer is multifaceted and crucial in driving the implementation of I2ROCs strategies within an organisation. This executive champion oversees and coordinates various initiatives related to remote operations, digital transformation, and the integration of human–machine collaboration. The Chief I2ROCs Officer will play a pivotal role in aligning the organisation's objectives with the I2ROCs vision, setting strategic direction, and ensuring the successful execution of initiatives.

Chief I2ROCs Officers are responsible for fostering a culture of innovation, collaboration, and continuous improvement within the organisation. They work closely with cross-functional teams and stakeholders to identify opportunities for remote operations optimisation, efficiency gains, and enhanced safety. Leading these initiatives, the Chief I2ROCs Officer ensures the company stays on the cutting edge of technical developments and adopts best practices for remote operations. Chief I2ROCs Officers also link the operational teams and executive leadership, highlighting the advantages, difficulties, and advancements of the I2ROC initiatives. They promote the provision of the funds, assistance, and investments needed to launch and maintain initiatives for remote operations. They can encourage a shared vision and a collaborative mindset by advocating for these ideas and gaining support and dedication from all organisational levels.

### 6.3. *Use of ROC-based training for new staff and reskilling for existing staff*

For mining organisations to remain competitive in the face of continuous technological advancements, they must have the right expertise within their workforce. Existing staff members must understand and appreciate how their work contributes to the organisation's overall sustainability. Additionally, employees should be made aware of how their reskilling and upskilling efforts can add value to the organisation. To achieve this, the industry should seize the opportunities presented by digital transformation and develop dedicated training based on ROCs. ROCs provide an ideal platform for delivering training programs to both new and existing staff members. These training programs can focus on various aspects of remote operations, digital technologies, and the integration of human–machine collaboration. Mining companies may foster a culture of ongoing learning and development where employees have the ability to succeed in the changing mining environment by employing ROC-based training. For existing staff, ROC-based training offer opportunities for reskilling and upskilling. These programs can be tailored to address specific skill gaps and align with the organisation's digital transformation strategies. Mining businesses can improve the skills of their personnel, empowering them to adopt new technology and make valuable contributions to remote operations and I2ROCs, by providing targeted training. For new hires, ROC-based training should be incorporated immediately to ensure they are adequately trained and on board with the company's digital vision. Mining businesses can instil the correct culture, values, and skill sets in new hires by incorporating this training into the onboarding procedure. This facilitates a smooth transition for new hires and fosters a cohesive and knowledgeable workforce. The use of ROC-based training also promotes collaboration and knowledge sharing among employees. Staff members can benefit from each other's experiences, share best practices, and collaboratively promote innovation inside the company by utilising the interactive and immersive nature of this training. This collaborative approach strengthens the organisation's overall capabilities and enhances its ability to adapt to new challenges and opportunities.

### 6.4. *Focus on people-centric technology*

In the pursuit of I2ROCs, it is crucial to prioritise people-centric technology that emphasises the intelligent interaction between humans and machines. While cost savings and increased productivity are undeniable benefits of remote operations and automation, the I2ROC concept recognises the value of human participants as key assets. Therefore, the technologies and techniques adopted and developed should enhance human creativity and abilities and overcome limitations.

The planning process for I2ROCs can be divided into three phases depicted in Fig. 7.

- Phase 1 focuses on establishing the fundamentals. This includes implementing technological platforms with appropriate redundancy to ensure reliability and resilience. It also provides comprehensive academic and industry-specific training to equip employees with the necessary skills and knowledge. In addition, fostering a culture that embraces adopting new technologies is essential at this stage.
- Phase 2 centres around empowering integrated teams. This entails providing teams with a single source of truth where accurate and up-to-date information is readily accessible. Knowledge sharing and collaborative work approaches are emphasised to encourage effective communication and collaboration among team members. The team's aggregate knowledge and experiences can be used to improve the organisation's decision-making and problem-solving processes.
- Phase 3 involves iterative optimisation procedures to continuously improve the capabilities of various functions, ultimately leading to the attainment of I2ROC status. This phase emphasises a culture of continuous improvement, where feedback loops and data-driven insights drive innovation and refinement of remote operations strategies. Mining businesses may remain at the forefront of developments and guarantee that their I2ROCs continue to develop and improve by routinely assessing and optimising processes, technologies, and workflows.

Throughout all phases, the focus remains on the human element, recognising that technology should augment and empower human capabilities. The aim is to create an environment where humans and machines collaborate intelligently, leveraging the strengths of both to achieve optimal outcomes. Mining organisations may unlock the full potential of ROCs by putting people at the centre of technical

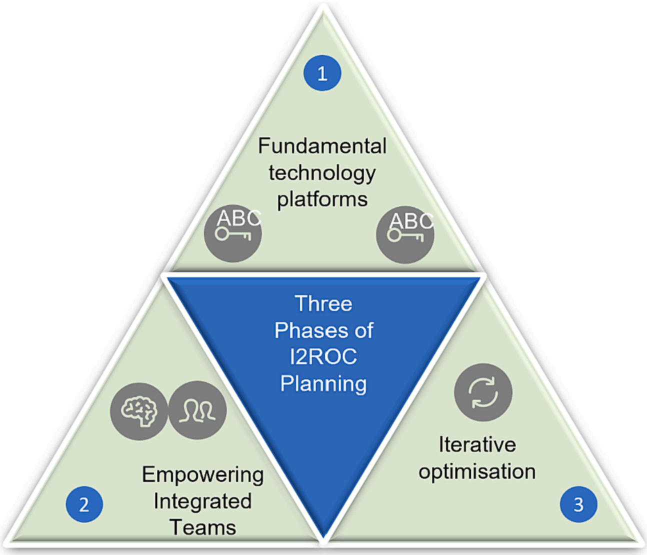

**Fig. 7.** Fundamental planning phases of I2ROCs.

development and execution while also assisting and upgrading the skills of their workforce.

## 7. Conclusion

The digital transformation journey in the minerals industry presents both challenges and opportunities. While the pace of mine modernisation may be affected by these challenges, stakeholders need to invest resources in managing mine operations during the transitional period. Developing ROCs with increased intelligence will be instrumental in improving the industry's performance metrics. Achieving I2ROCs is a progressive and iterative process, with milestones to be reached along the way. Empowering staff through digital training, fostering research collaborations between industry and academic institutions, and appointing dedicated mine champions for I2ROCs are vital steps in this journey. The ultimate goal is to achieve strong AI capabilities, but it requires strategic planning and implementation. Shareholders and stakeholders must recognise the long-term nature of the transitional period and invest in developing models and strategies to manage mine operations during this time effectively. The mining business may boost its performance, increase efficiency, and promote sustainable growth by embracing digital transformation and implementing novel ideas. This work has outlined the critical fundamentals towards developing strategies for I2ROCs, providing a foundation for stakeholders to refine further and advance their initiatives. With a focus on human–machine collaboration, continuous learning and development, and the integration of advanced technologies, the minerals industry can navigate the complexities of digital transformation and pave the way towards a self-governed and intelligent mining landscape.

## CRediT authorship contribution statement

**Mulundumina Shimaponda-Nawa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Glen T. Nwaila:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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