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International Journal of Mining, Reclamation and Environment

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/nsme20

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To cite this article: Tawanda Zvarivadza, Moshood Onifade, Oluwatobi Dayo-Olupona, Khadija Omar Said, Joseph Muchiri Githiria, Bekir Genc & Turgay Celik (2024) On the impact of Industrial Internet of Things (IIoT) - mining sector perspectives, International Journal of Mining, Reclamation and Environment, 38:10, 771-809, DOI: 10.1080/17480930.2024.2347131

To link to this article: https://doi.org/10.1080/17480930.2024.2347131

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Published online: 07 May 2024.

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INTERNATIONAL JOURNAL OF MINING, RECLAMATION AND ENVIRONMENT
2024, VOL. 38, NO. 10, 771–809
https://doi.org/10.1080/17480930.2024.2347131

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On the impact of Industrial Internet of Things (IIoT) - mining sector perspectives

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ABSTRACT

The application of the Internet of Things (IoT) in industrial systems and other new technological advancements led to the development of the Industrial Internet of Things (IIoT). IIoT can help overcome the shortcomings of the conventional monitoring and control system while enabling enterprises to create a unified monitoring system to automate operations, provide a safe working environment, enforce compliance effectively, and regulate environmental issues. Given the advantages that IoT brings to the forefront, it makes sense that so many mining companies have raised their investment following the implementation of IoT-enabled solutions in their organisations. To increase safety, productivity, and environmental sustainability in mining operations, this article examines the current state of information technology in the mineral industry with an emphasis on the implications and challenges brought on by the technological diversity of various systems and devices used in those activities. The study contributes valuable insights into the integration of IoT technologies in the mining industry, highlighting its potential to improve safety, efficiency, and sustainability. The paper paves the way for future research and development efforts aimed at overcoming the challenges of adopting IIoT in mining operations by identifying gaps and proposing a comprehensive IoT architecture. The innovations of the study are encapsulated in its approach to detailing the application of IoT technologies in enhancing mining operations and the establishment of an overall IIoT architecture suitable for the general operations in the mining industry.

ARTICLE HISTORY
Received 7 December 2023
Accepted 18 April 2024

KEYWORDS
Industrial IoT; smart machines; wireless communication; sensors, tracking devices; mining technology; mining digitization

1. Introduction

One of the most important areas of future technology is the Internet of Things (IoT), which is attracting a lot of attention from different types of enterprises. IoT is the network of physical devices, vehicles, machinery, buildings, and other structures that are connected to the internet to collect and share data to be used for further analysis. The true value of the IoT for businesses can be fully realised when connected devices can communicate with each other and integrate with systems

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for vendor-managed inventory, business analytics, business intelligence applications, and customer support [1,2]. The IoT is expected to grow from 0.9 billion units in 2009 to 26 billion units by 2020, according to Gartner [3]. This development will affect the information that supply chain participants can access and the way the supply chain runs. By enabling more accurate and real-time visibility into the measure of goods and services, the IoT is innovating corporate processes.

The Industrial Internet of Things (IIoT) is one of the key components of Industry 4.0. By utilising the capabilities of smart machines and real-time analysis, IIoT maximises the use of the data that industrial machines have been creating for years [2,4]. IIoT is primarily powered by smart machines for two reasons [5]. First of all, in contrast to people, intelligent robots are able to gather and analyse data instantly. Secondly, intelligent machines can convey their conclusions in a clear and concise manner, facilitating the making of speedier and more accurate business decisions.

A significant transformation in mining is taking place as a result of the quick growth of information technologies [6–8]. The idea of a 'smart mine' has been put up to support safety, environmentally friendly and productive mining operations, and it has garnered considerable interest from both the mining industry and academics [9]. According to Lyu et al. [10], a smart mine should be capable of (a) integrating component software, transmission networks, different sensors, etc., (b) creating a network of intelligent systems capable of actively sensing, automatically analysing, and implementing the best control possible over different mining operations and it should also be able to realise safe, cost-effective, automated and environmentally friendly mining processes.

The IoT, a technological paradigm, proposes a worldwide network where machines or items can talk to one another [1]. It is projected that between 50 and 100 billion smart objects and entities will be online by 2020 [11]. Given the possibility for historically large-scale production system changes, industries are being forced to reconsider their production methods [7,12]. The market for IoT in mining was estimated to be worth US$1.4 billion in 2020 and is anticipated to expand at a compound annual growth rate (CAGR) of more than 6% from 2021 to 2025. Over the projected period, the mining sector's IoT software revenue will expand more quickly than that of other industries. Revenues from IoT hardware will increase at a CAGR of over 7%, while those from IoT services will rise more slowly at a CAGR of over 3% [13].

The advantages of traditional industry are combined with internet technologies [14,15] in the Industry 4.0 concept, which highlights the idea of constant digitisation and the connectedness of all producing units [16]. This idea includes the IIoT, which is an IoT application in industry. In order to generate greater value and service, the IIoT is a network of physical items, or things, that are implanted with electronics, sensors, and connections. This enables the network to share data with the maker, operator, and/or other connected devices [17]. Currently, a wide range of IoT technologies are used in consumer applications such as connected cars, smart homes, and smart wearables. However, it is anticipated that industrial IoT or IIoT applications would change a wide range of industries, including mining, manufacturing, agriculture, construction, and oil and gas [18–20].

Over time, mining methods and technologies have changed and advanced. Every technological development that was applied at mine sites in the past led to enhanced procedures and notable industrial growth. The vocabulary used to describe these technological breakthroughs and the subsequent changes they will bring about for the mining industry on the implementation of transformational technologies has grown quickly at conferences, in the media, and online [21,22]. With automation, wireless communication, telemetry and remote visibility, the IoT is driving the mining industry's digital transformation [23]. Any communication breakdown could have severe effects on both company operations and human lives in the mining sector. IoT technology guarantees effective communication, cost reduction in mining operations, and high profits while maintaining workers' safety. IoT is now being used by numerous governments and mining industries for real-time data performance planning, deployment, and improvement. They employ the technology for precise data monitoring and analysis in order to develop a strategic business plan [24].

Mobile equipment coordination is facilitated in the mining industry by the use of IoT to track truck location and loading status. In case of an emergency, there are other technologies to track individuals [25]. In underground mines, IoT monitoring systems are also used to track the stability and mobility of the rock [26]. IoT, in particular, enables the interconnection of inexpensive sensors to work as a cross-platform system and provide data to a central location [27]. The IoT and IIoT share the same functional principles, while the IIoT has been specifically designed for industrial usage. The IIoT is centred on complex, always-on, data-intensive systems. According to Aazam et al. [28], the components of an IIoT system, such as wireless sensor network (WSN), big data, cyber-physical systems, and virtual sensing are the main pillars of such a platform. IIoT is employed at mine sites to record and monitor tailings dam characteristics, such as wall movement and water level [29].

Mining companies are now able to operate mines more safely, more productively, and more affordably because of improved data collection and analysis via sensors and the internet. Wearable technology, driverless transport trucks, predictive maintenance, drones for surveying and autonomous drilling are a few examples [30–32]. By combining and connecting big data, analytical tools, wireless networks, and physical and industrial equipment, the Industrial IoT uses meta-level networking characteristics to distribute systems. By providing internet connectivity and sensors to workers, machines, and vehicles, mining businesses can increase productivity, safety and efficiency at the mine site [20,33]. In consequence, improvements in productivity and efficiency aid in the reduction of carbon emissions [34].

Currently, the mining industry's innovative processes and digital technologies' general direction and structure, as well as the motivating forces behind the adoption of these technologies have been identified [35,36]. Specialised digital technologies have already been documented by van Duin et al. [37], Groenveld and Rozou [38], and others, and are particularly relevant for mineral processing and beneficiation. However, an evaluation of IIoT applications and its implementation in the mining industry is not well-known. Therefore in this article, the impacts and drawbacks of IIoT have been highlighted, along with their application in actual mining operations and an overall IoT architecture suitable for the general operations in the mining industry, covering areas such as mine planning, mineral resource estimation, rock mechanics and geotechnical engineering, mine ventilation, fleet, and personnel management is established. With emphasis on mine planning, mineral resource estimation, rock mechanics and geotechnical engineering, mine ventilation, fleet and personnel management, and mine surveying. In addition, the paper has examined the IIoT usage patterns currently prevalent in several mining operations and the developed IIoT architectures appropriate for these operations.

Figure 1 illustrates how data flows from the mine to the decision-makers. It starts with data collection (from various sensors in the mine), data transmission (via communication networks), data processing and analysis, and finally, decision-making based on the analysed data.

The main objective of this study is to examine the current state of IoT in the mining industry, with a focus on the implications and challenges brought about by the technological diversity of various IoT systems and devices used in mining activities. The study explores how IoT can help overcome the shortcomings of conventional monitoring and control systems by creating a unified monitoring system that automates operations, provides a safe working environment, enforces compliance effectively, and regulates environmental issues.

The innovations of the study are encapsulated in its approach to detailing the application of IoT technologies in enhancing mining operations. The study's proposal of an IoT architecture that is suitable for mining operations represents a significant step forward in conceptualising how various IoT components can be integrated into a cohesive system that addresses the unique needs of the mining industry.

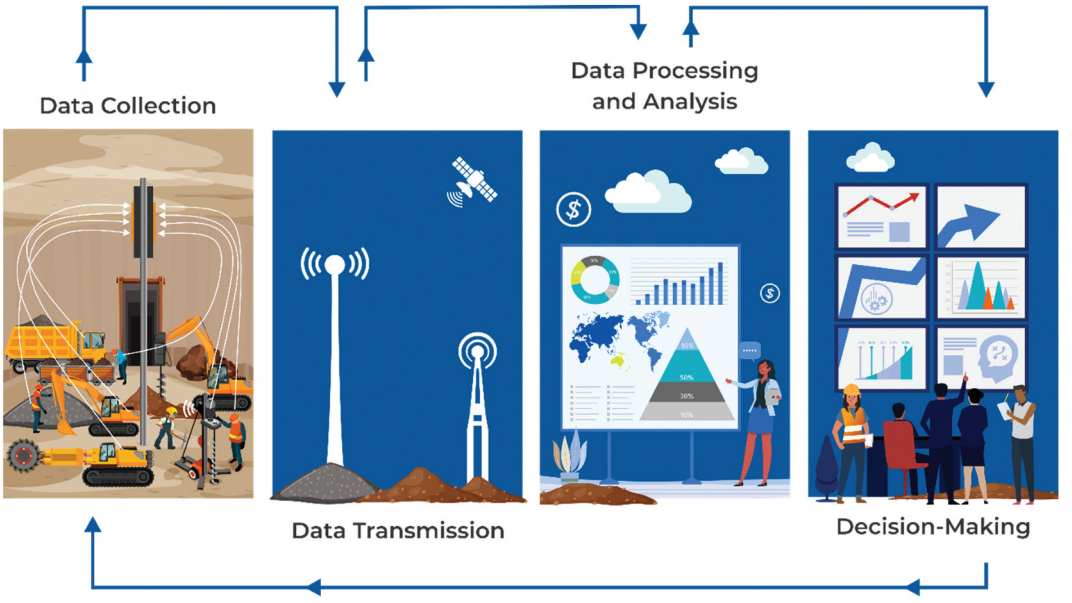


Figure 1. Data process flow diagram of IIoT in mining.

2. Benefits of implementing IoT technology in the mining industry

Many different industries, including energy, mining, oil and gas, manufacturing, transportation, aviation, and logistics utilise the IIoT. Its main goal is to optimise operations, particularly maintenance and process automation. IoT capabilities improve asset performance, allow for improved maintenance management, and facilitate and organise the mining process. The IoT technology supports sensors that gather important data, evaluate it in real-time, and share the best course of action for a mining operation. Some advantages of using IoT technology in the mining industry are discussed below.

Figure 2 presents an infographic that encapsulates the benefits of implementing IoT technology in the mining industry as discussed below. The central icon is a stylised representation of a mining helmet, partitioned into four sections, each symbolising a distinct advantage of IoT technology. These include predictive maintenance and productivity analytics, energy and cost efficiency, improved safety, time efficiency and increased profitability in the operations.

2.1. Automated mining techniques

More data is acquired when vehicles and equipment work together, consequently increasing the accuracy rates. By using technology to filter the data and focus on the important information, mining businesses can ensure intelligent planning. The newest IoT-enabled products and their updates speed up and increase the profitability of the mining cycle [39,40]. The more data obtained while using self-standing products, such as a functioning vehicle and equipment, the higher the accuracy rates [23]. IoT enables mining companies to discover the newest breakthroughs, technologies, development trends, and market-leading strategies.

2.2. Increased energy savings and cost effectiveness

Better efficiency is guaranteed by an IoT system with mining safety measures in place. IoT-based solutions allow mining personnel to become more productive, which optimises how much energy

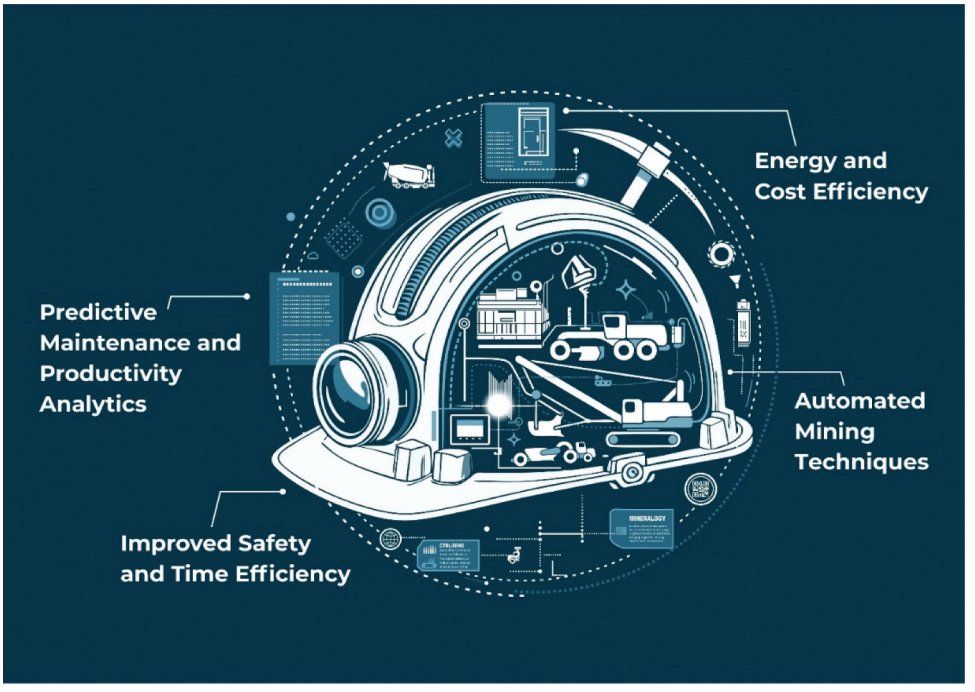


Figure 2. Benefits of implementing IoT technology in the mining industry.

and money are used [24]. Companies all across the world are seeing fewer accidents, employee complaints, little human error, and other issues as a result of the IoT [41]. On the other hand, the cost savings can be put towards corporate expansion, and the energy saved can go towards creating a more environmentally friendly future. Energy use is reduced while mining industry costs are maintained due to investments in the IIoT.

IIoT-driven ventilation control systems introduce energy efficiency into mining operations. By adjusting fan speeds and airflow in real-time based on actual needs, they significantly reduce energy consumption and operational costs. This leads to substantial cost savings without compromising on safety or air quality. Additionally, they have a transparent system where every component is watched, which makes the process more effective. This is still growing, the price of employing new staff is getting cheaper, and it helps the industry become more lucrative.

2.3. Enhanced safety and time saving during mining processes

Even in the modern age, the mining industry is quite hazardous. Mining depths needed for mineral or precious metal extraction pose a number of serious challenges to mine workers, including cave-ins due to geological instability, heat and toxic fumes. When working in industrial environments with harsh temperatures, isolated locations, pressure changes, deep mines, and the presence of heavy equipment, mine workers are more likely to experience health problems and accidents. Mining companies are accountable for making sure that personnel are adequately protected while on the job site by actively preventing accidents and monitoring safety.

Installed sensors in both surface and underground mines identify damaged equipment and foresee potential problem locations, predicting system instability and malfunction in mine access such as shafts. This understanding aids in maintaining and averting any accidents that might typically happen as a result of ignorance or resource extraction [40]. Additionally, IoT-based automated technologies like self-driving cars offer vital information regarding the areas being

mined [23]. This information is used by large mining companies to safely plan and carry out their activities. IoT reduces overhead costs for the business, saves time, and assures seamless project execution through technologically based safety improvements and resource extraction.

IoT is very helpful in developing and sustaining mine sites. Before mining excavation starts, data is gathered to make sure the process is controlled effectively. Large mining companies are experimenting with autonomous drilling technologies and using driverless vehicles in some of their operations without human intervention [5,33]. Because of this, the minerals may be removed and processed more quickly. IoT is beneficial for creating and maintaining the mine site.

2.4. Predictive analytics for active maintenance and productivity

Data-based prediction helps large mining companies make decisions that are reasonable and well-informed. Everything is monitored by sensors, and IoT-integrated systems make sure that there is open communication in the environment, enabling a productive situation. A fully connected network makes it easier to see wear and tear on important pieces of equipment and make estimates about when repairs or maintenance are necessary. As a result, there is no risk, less downtime, less expense, and higher safety and productivity [30,39].

Increased productivity means increased production which increases the project value of the mining operation. Availability and utilisation analysis of the mining machinery incorporated by economic analysis of the entire mining operation can be integrated and optimised using IoT systems. The outcome from such a system will produce an optimal production schedule in both long-term and short-term plans to maximise profits. Miners must make sure their output is rising by implementing the latest technologies. Monitoring and automation help to increase output while reducing costs per unit of output.

The whole mining value chain, from prospecting to reclamation, offers prospects for IoT implementation and operation improvement [40]. Proximity detection sensors on moving machineries and vehicles, wearable technology, scanners to identify different ore grades and transmit this information across the mining value chain and drones are just a few examples of devices that can result in modest but cumulative productivity benefits. The ability to adopt IoT throughout the entire value chain is being aided by the declining cost of sensors and increased processing power [30,34]. The environmental, social and governance (ESG) credentials of an organisation can be improved by using machine data to increase production and efficiency, which in turn can assist to minimise emissions. Environment, one of ESG pillars, can also be improved by IoT devices like wearable technology and proximity detection.

3. Implementation of IoT in the mining industry

Numerous industry- and user-specific IoT applications are growing faster due to the IoT. While devices and networks provide physical connectivity, IoTs applications enable trustworthy and robust interactions between humans and machines. Hardware-based IoT applications need to verify that messages and data have been received and are being handled correctly and quickly.

Any sector that produces tangible things or manages their transportation might benefit greatly from IIoT. IIoT has the potential to increase operational effectiveness, which creates opportunities for completely new business models. It can be applied to numerous businesses across a wide range of industries. Using IIoT technology, most building management issues may be resolved. Sensor-driven climate control considers all relevant factors, such as the locations of ventilation, machinery, people count, and other factors, and removes any uncertainty related to regulating a building's internal climate i.e. ventilation on demand concept [24,24]. IIoT enhances building security with smart devices that assess possible threats from any point of entry into the facility.

The production industry is currently where IIoT technology is most commonly utilised. IIoT-capable intelligent equipment can self-monitor and anticipate possible production bottlenecks [33].

Efficiency rises as a result, and downtime is decreased. Sustaining production levels is important, but effective supply chain delivery is just as important. With IIoT, orders can replace stocks automatically as needed [5]. This reduces waste, maintains stock levels, and ensures that the right amount of raw materials are constantly available. Because supply chains and ordering are automated, workers can focus on more intricate aspects of their jobs.

IoT-enabled technologies are developing quickly, and many developments that will occur in the future will influence the history of the mining industry. Networking, analytics, and data are the heart of the IoT. Many mining companies have operations that range from exploration to importation of the mined products. They employ large machinery and rely heavily on employees who either operate underground or in climate-controlled offices. The mining sector is undergoing change, creating an efficient environment to be on the lookout for. In this section, this paper talks about how IoT is transforming the mining industry fundamentally by enhancing safety and productivity through control systems.

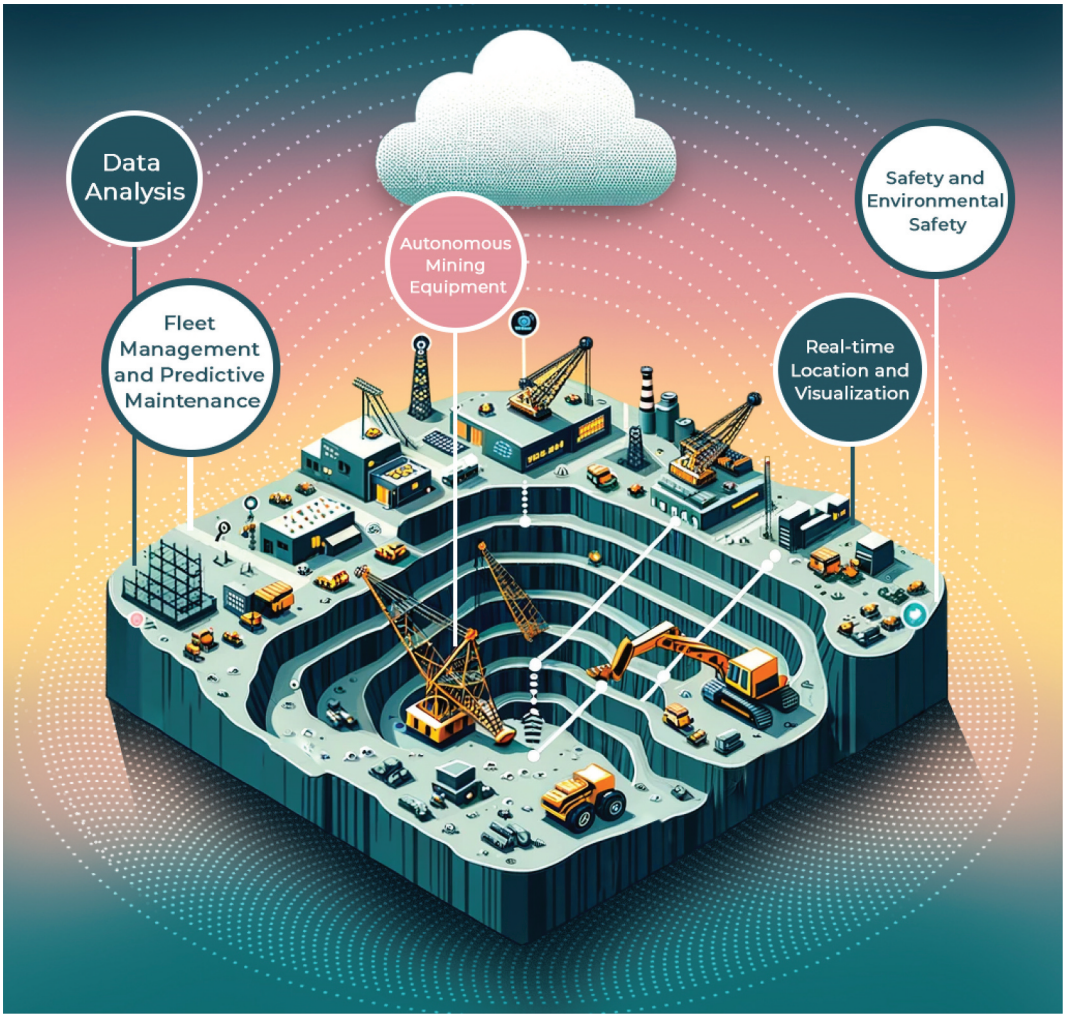


Figure 3. Implementation of IoT in the mining industry.

The infographic in Figure 3 presents an overview of the IoT applications within the mining industry. The infographic depicts a mining site, illustrating the integration of various IoT technologies. These technologies play pivotal roles in diverse aspects of mining operations. They facilitate efficient data analysis, enable predictive maintenance, operate autonomous equipment, and allow real-time tracking of assets.

3.1. Data description and analysis

IoT devices collect data in real-time, making it easier to identify and fix problems. This makes it possible to monitor the entire mining operation. Since machine learning techniques take into account all geological factors before identifying a drilling area, many businesses utilise it to optimise the mining process by choosing a drilling area where the necessary ore is present in large quantities [42]. Every system has data that is stored and then displayed to engineers and managers as a graph or chart. One industry that has profited greatly from IoT devices is mining since they allow for remote monitoring of employees and equipment using in-mine wireless networks [40,41]. This aids in improving safety in their working environment.

The data's analytical results are very helpful for examining many aspects that influence business and technical decisions. The large-scale mining industry benefits greatly from analysis. The management can assess each system's effectiveness and take appropriate action. By assessing the strength of the mine that has been developed, which is done by examining the vibrations in the earth, the safety of the workers is also guaranteed [31].

3.2. Sensors on mining equipment and machinery

The mining equipment has IoT sensors installed to offer information about the machine's condition and operational state. The technology assists mining operations in measuring temperature inside the mine, the strength of ground vibrations, air pollution levels, and other variables. Predictive maintenance is used by the equipment sensors to protect workers and reduce the expense of frequent repairs. This assistance allows the mining company to plan repair of tools and equipment in advance of their failure or breakdown [5]. Accidents can be avoided and workers can avoid becoming sick, hurting themselves, or even dying due to prompt maintenance [39]. IoT offers the mining industry and its employees a win-win situation.

IoT enhances fleet visibility and management. From a centralised location, businesses can monitor and control their machinery. With the use of 5 G transmission technology, the fleet's locations can be precisely tracked and monitored. Theft incidents, waste, unauthorised entrance, and other issues are decreased due to effective truck tracking and control [39]. Additionally, it reduces costs for mining activities and guarantees the security of the employees.

3.3. Real-time locating systems and visualisation platforms

IoT sensors use radio-frequency (RF) locating, radar and Global Positioning System (GPS) technologies to locate nearby heavy machinery or vehicles in order to prevent accidents in mines. Mining workers utilise this knowledge to safeguard themselves and their co-workers against mishaps that could result in fatalities [34,39,43]. The fact is that a mining company's profitability is directly correlated with a worker's safety. Companies pay less on healthcare and equipment upkeep when employees are safe, which results in huge savings that can be put towards other business endeavours.

Mines are big places to operate, plan, and traverse. IoT technologies, which use cutting-edge and precise instruments like sensors and GPS, have simplified the mine planning process. Businesses now have access to more data due to Big Data visualisation, which enables them to develop educated

and confident business plans and so successfully complete mining operations [5,20]. In order to understand the layout, navigate, manage operations, and troubleshoot any emergencies, drill and blast crews, mining engineers, and business managers employ IoT-enabled software to construct a 3D map of the mine. The mining operations are safer, there are fewer risks of workers being exposed to dangerous surroundings, and the activities are more cost-effective with a strategic plan that includes accurate, real-time data and 3D maps.

3.4. Safety and environmental protection

IoT devices will be able to create effective mine planning using the obtained data, which will assist managers in making decisions in accordance with the suggested mine plan. The provided mine design is regarded as the most effective plan because it takes into account all the important factors affecting the working environment. The sensors pinpoint the precise position of the problem and raise an alarm to draw attention to it right away [22,41] hence avoiding major accidents.

Every industry has safety as one of its top considerations, but mining industry has the highest risk to human life because of the complex working environment, especially in underground mines. With the provision of reliable data that is utilised to protect worker safety, for example, by forecasting the structural stability of mines, IoT has influenced the way that safety is seen. In order to conduct mining activities in hazardous areas, a variety of IoT devices, such as drones and robots, are used. IoT devices may gather data on variables including gases, pressure, vibrations, temperature, and humidity. These metrics can be monitored in real time, and any changes can be recorded [23,34].

Mines frequently become contaminated since they are full of dangerous substances and lethal gases [44]. These problems can slow down operations, make employees sick, or even kill them from extreme exposure. The mining company's overhead costs go up as a result of the dangerous environments, which also cause human casualties. The amount of contamination at a specific place can now be determined and the ventilation system may be adjusted accordingly due to an IoT-based effective ventilation system [ventilation on demand (VOD)] [34,44]. The mining company can guarantee the safety of the underground miners who can benefit from enhanced safety benefits without placing themselves in potentially dangerous conditions because the ventilators are remotely controlled via the internet.

3.5. Autonomous mine equipment

Mining is now safer and more economical due to autonomous equipment and vehicles that are IoT equipped. These devices operate the self-driving vehicles and machinery remotely over a high-bandwidth internet connection from kilometres away, protecting workers from danger. This equipment can find their way through a mine and react to whatever situation they come across. Remote-controlled excavators, teleoperated bulldozers, remote-controlled bulldozers, self-driving trains and teleoperated excavators are examples of self-driving vehicles. Another development in the direction of a safer workplace in mines is IoT wearables. For improved communication and handling of emergencies like gas leak, mine fire, and workers' levels of weariness, employers are encouraging staff to wear these devices [4,30]. Due to such control systems, a mining company can increase efficiency and subsequently increase its high revenue with fewer accidents [41,42].

4. Current use cases of IoT in the mining industry

The mining industry, a cornerstone of global resource supply and economic development, has long been associated with the extraction of essential raw materials that power modern society. From precious metals to industrial minerals, the sector has traditionally faced unique operational challenges and complexities. The imperative approach to enhance efficiency, safety, and



Figure 4. Use case study (rock mechanics and geotechnical engineering, mine ventilation and fleet management).

sustainability has led to a fundamental shift in how mining operations are conducted, and at the heart of this transformation is the IoT. IoT represents a technological modernisation with the potential to redefine and optimise mining practices across various domains [4,45]. The combination of sensors, data analytics, and real-time connectivity has opened the doors to a new era in mining, where data-driven decision-making, automation, and improved safety converge to enhance every facet of the industry. This section provides an in-depth exploration of how IoT is harnessed in the mining industry, touching upon key areas such as mine planning, mineral resource estimation, rock mechanics and geotechnical engineering, mine ventilation, fleet and personnel management, and mine surveying.

This infographic (Figures 4 and 5), in a horizontal layout, highlights the current use cases of IoT in the mining industry. Each section focuses on a specific application area explicitly discussed in Sections 4.1 to 4.6. For example, the 'IoT in Mineral Resource Estimation' section itemises four (4) use case areas within that operational phase of mining. Both figures present a summary of the overall benefits of IoT in mining, reinforcing the key points.

4.1. IoT in mine surveying

Mine surveying is the cornerstone of successful mining operations by pioneering precision in locating the mining boundaries thus improving efficiency in both surface and underground mine operations. It involves mapping and monitoring underground structures to ensure accurate excavation and adherence to mining plans. Traditionally, this process relied on manual measurements and surveys, with limited real-time capabilities. However, the advent of the IoT has propelled mine surveying into a new era. IoT technologies have overhauled surveying by providing real-time, accurate, and efficient data collection and analysis capabilities. IoT-driven surveying reduces labour costs and minimises the need for rework due to errors. The precision and accuracy of IoT-based surveying data reduce the likelihood of costly mistakes in excavation and planning. By streamlining surveying processes, IoT ultimately contributes to cost savings. This section further discusses the profound impact of IoT in mine surveying, exploring key applications and the multidimensional benefits it brings to the mining industry.



Figure 5. Limitation of using IOT in the mining industry.

4.1.1. IoT applications in mine surveying

4.1.1.1. 3D mapping and scanning. IoT-equipped Light Detection and Ranging (LiDAR) and laser scanning devices are transforming the landscape of mine surveying [46–48]. These devices create highly detailed 3D maps of underground environments, aiding in precise surveying. LiDAR and laser scanning devices emit laser beams that bounce off surfaces and return data about the distance and shape of objects. These devices are typically mounted on mobile platforms such as drones or robotic vehicles, allowing them to navigate underground spaces. The data they collect is used to create intricate 3D models of the mine's interior. 3D mapping and scanning with IoT technology provide unparalleled precision and detail. These maps are essential for creating accurate representations of mine structures, understanding geological features, and optimising excavation processes.

4.1.1.2. Drones and UAVs. IoT-enabled drones and unmanned aerial vehicles (UAVs) have rapidly become integral to mine surveying. These devices capture high-resolution images and data for surveying and mapping applications. Drones equipped with IoT technology can access areas that are challenging for humans to reach, including shaft monitoring, steep slopes and unstable terrain. They capture images and data that are then processed to create topographic maps, orthomosaics, and 3D models of the mining site. The real-time data and imagery collected by drones and UAVs are indispensable for mine surveying tasks such as volume calculations, asset tracking, and environmental monitoring. They provide a bird's-eye view of the mine, aiding in decision-making and planning.

4.1.1.3. Real-time data integration. IoT systems collect real-time data from various sources, including surveying instruments and geological sensors, to provide a holistic view of the mining environment. This integration of data is central to accurate and efficient mine surveying. For example, data from surveying instruments can be combined with geological sensor data that tracks

ground movement and subsidence. The resulting dataset offers insights into the stability of the mine and helps surveyors make informed decisions about excavation and support systems. Real-time data integration with IoT enhances the surveying process by providing a comprehensive and up-to-date understanding of the mine's conditions [4,49]. IoT technologies significantly enhance the precision and accuracy of mine surveying. The detailed 3D maps and real-time data integration ensure that surveyors have access to the most accurate information when making decisions about mining plans and safety measures. The risk of errors in mapping and planning is greatly reduced.

4.1.1.4. Automated data analysis. IoT facilitates the automated analysis of surveying data [25,50]. It streamlines the generation of accurate maps and models, reducing the manual effort required for data processing. Advanced algorithms and machine learning models can process data from various sources, automatically aligning and fusing information to create detailed maps. These maps can be updated in real time, allowing surveyors to make immediate adjustments to mining plans. Automated data analysis with IoT reduces the time and effort required for surveying tasks. It also minimises the risk of human errors, ensuring that surveying data is consistently accurate.

4.1.2. Keynote on IoT in mine surveying

The incorporation of IoT technologies into mine surveying has reinvented the field, introducing precision, efficiency, and cost-effectiveness into mining operations. IoT applications, including 3D mapping and scanning, drones and UAVs, real-time data integration, and automated data analysis, are reshaping the way surveying is conducted in mines. The benefits of IoT in mine surveying are substantial, encompassing enhanced precision and accuracy, time efficiency, and cost savings. IoT technologies ensure that surveyors have access to the most accurate and up-to-date information, reducing errors in mapping and planning. They also expedite surveying tasks, allowing mining operations to make swift and informed decisions. As the mining industry continues to evolve, IoT technologies are poised to play an even more significant role in shaping the future of mine surveying, ultimately contributing to safer, more efficient, and cost-effective mining practices.

4.2. IoT in mineral resource estimation

Mineral resource estimation stands as a cornerstone in the mining industry, guiding critical decisions about the viability and economic potential of deposits. Traditionally, this process also heavily relied on manual data collection and predictive models. However, with the advent of the IoT, mineral resource estimation has entered a new era. IoT technologies are transforming this crucial aspect of mining by enhancing data collection, analysis, and resource modelling. Resource modelling involves conversion of geological data generated from exploratory works into a robust orebody model that dynamically changes timely and accurately as information is updated. This section discusses the significant impact of IoT in mineral resource estimation, exploring key applications and the different benefits it offers to the mining industry.

4.2.1. IoT applications in mineral resource estimation

4.2.1.1. Automated drilling and sampling. One of the critical steps in mineral resource estimation is the collection of samples from the mining site. Traditionally, this process was labour-intensive and often led to variations in sample quality due to human error. IoT technologies have introduced a paradigm shift by enabling the automation of drilling and sampling processes. IoT-equipped drilling equipment, often integrated with robotics and artificial intelligence (AI), can autonomously extract samples with precision and consistency. These automated systems follow predefined patterns and extract samples at predetermined intervals. The collected samples are then tagged with real-time data, such as depth and location, and seamlessly integrated into the resource estimation models. The integration of IoT-driven automated drilling and sampling not only enhances the precision and consistency of sample collection but also reduces the potential for

contamination and human errors [22]. This leads to a higher quality dataset for mineral resource estimation.

4.2.1.2. Remote sensing and drones. Remote sensing technologies such as photogrammetry and laser scanning devices, combined with IoT-driven drones, are modernising the identification and characterisation of mineral deposits, significantly aiding in resource estimation. IoT-equipped drones, equipped with advanced remote sensing technologies, can collect high-resolution images and spectral data from the mining site. These sensors are capable of detecting unique signatures of minerals, allowing for the identification of potential deposits. This aerial perspective provides resource estimators with a holistic view of the mining area and enables them to identify mineralisation patterns that may not be readily apparent from ground-level observations. The high-resolution imagery and spectral data gathered by IoT-driven drones are invaluable for resource estimators. They provide a real-time view of the site's mineralogical composition, facilitating a more accurate resource model.

4.2.1.3. Data integration and analysis. Mineral resource estimation relies on the integration of diverse datasets, including those generated from drilling, remote sensing, geophysical, and geological surveys. IoT plays a pivotal role in this integration by seamlessly connecting various data sources. IoT systems collect data from drilling equipment, geophysical sensors, remote sensing devices, and geological surveys [49]. This data is then collated and integrated into a comprehensive dataset, forming the foundation for resource estimation models. IoT-driven data integration ensures that resource estimators are working with up-to-date and high-quality information. Additionally, IoT facilitates data analysis. Advanced algorithms and machine learning models can be applied to the integrated dataset for pattern recognition, anomaly detection, and predictive modelling. These analyses provide insights into mineralisation trends, ore distribution, and deposit variations, contributing to more accurate resource estimates.

4.2.2. Keynote on IoT in mineral resource estimation

The integration of IoT in mineral resource estimation significantly enhances the accuracy of resource models. By automating drilling and sampling processes, IoT technologies reduce the potential for errors. This leads to a higher quality dataset, which in turn results in more precise resource estimates. Real-time monitoring of seismic and geophysical data also allows for adjustments in resource estimates as new information becomes available, minimising inaccuracies. The benefits of IoT in mineral resource estimation are diverse, encompassing improved accuracy, time and cost efficiency, and real-time monitoring. With IoT, resource estimators can make data-driven decisions, reduce estimation errors, and maintain resource models that align with current site conditions. The continuous monitoring of data from drilling, geophysical and geological surveys, and remote sensing ensures that resource models remain up-to-date and reflective of the evolving mining site conditions. This real-time aspect reduces the reliance on static data and the risk of working with outdated information.

4.3. IoT in mine planning and optimisation

Mine planning involves selection and coordination of all subsystems in a mining operation by incorporating the mine production capacity, equipment selection, costing and scheduling of the material mined. In the mining industry, the art of mine planning plays a pivotal role in determining the optimal utilisation of resources and the efficiency of the extraction process. Traditionally, mine planning has heavily relied on historical data and predictive models. However, with the advent of the IoT, the landscape of mine planning has undergone a profound transformation. IoT technologies have ushered in an era of data-driven decision-making, real-time monitoring, and resource

optimisation. This section delves into the significant impact of IoT in mine planning, exploring key applications and the manifold benefits it offers to the mining industry. IOT can be incorporated to optimise both surface and underground mine plan by integrating data from block model and other parameters (economic, geological and operational). This will define the pit limits, stope layouts, infrastructure and development placement, equipment selection and production scheduling with the aim of maximising profit.

4.3.1. IoT applications in mine planning

4.3.1.1. Sensors for geological data. One of the cornerstones of efficient mine planning is the availability of accurate geological data. IoT sensors, strategically deployed at mining and exploration sites, have emerged as indispensable tools for real-time data collection [50–52]. These sensors are capable of gathering a wealth of geological information, including ore quality, deposit size, and depth. This data is crucial for making informed decisions about the location and layout of mining operations. The data collected by these sensors is not static but is continuously updated. This real-time information allows mine planners to adjust their strategies dynamically in response to changing geological conditions. It minimises the reliance on historical data, which may not accurately reflect the current state of the mining site. Consequently, mine planners can design excavation methods that align with the latest geological insights, leading to more efficient resource utilisation and improved ore recovery rates.

4.3.1.2. Geospatial data analytics. Spatial and coordinate system is incorporated in the mine plan to locate the grade-tonnage distribution in the orebody model. This helps in setting up the mining boundaries of the deposit and subsequently defining the pit limits and stope layout. Mine planners depend on accurate topographic maps and models to design mine layouts, determine the optimal extraction methods, and assess potential environmental impacts. IoT technologies, specifically geospatial analytics, have reshaped the process of map and model creation. IoT devices, often integrated with high-resolution sensors such as LiDAR (Light Detection and Ranging) and drones, can generate detailed, accurate, and up-to-date topographic maps [48,53].

These maps offer a real-time view of the mining site's terrain, including surface irregularities, elevation changes, and geological features. The high-resolution images and data gathered by these devices provide a comprehensive and precise overview of the mining area. The real-time nature of this geospatial data is invaluable for mine planners. It ensures that mine planners are working with the most current information available, reducing the likelihood of inaccuracies and oversights. Moreover, it facilitates the early detection of any changes in the geological or environmental landscape, enabling prompt adjustments to the mine plan. This level of accuracy and flexibility contributes to more efficient mine designs and aids in preventing potential environmental impacts.

4.3.1.3. Monitoring ore movement. Efficient mine planning also hinges on the careful management of ore throughout the extraction process. The material mined is monitored to maintain a steady supply of material to the processing plant using both short and long-term plans. These plans have to follow both tactical and strategic plans in order to achieve the desired project value. IoT-enabled Radio-Frequency Identification (RFID) tags and GPS systems have become instrumental in monitoring the movement of ore from the point of extraction to processing facilities [43,54–56]. RFID tags, affixed to ore containers, allow for the continuous tracking of ore movements. These tags provide real-time information about the location and status of ore movements, ensuring that they are transported according to the mine plan. If any deviations occur, mine planners and operators are immediately alerted, allowing for rapid adjustments to ensure that ore movement aligns with the plan. GPS systems, integrated into mining equipment and vehicles, offer another layer of tracking and monitoring.

These systems provide precise information on the location of mining equipment and the movement of ore within the mine. They contribute to the overall coordination and synchronisation

of mining operations, reducing delays and inefficiencies. The ability to monitor ore movement in real time enhances mine planning in several ways. It prevents discrepancies between the plan and the actual execution, leading to higher resource recovery rates. Additionally, it facilitates the early identification of issues, enabling timely corrective measures.

4.3.2. Keynote on IoT in mine planning

The integration of IoT in mine planning results in a safer working environment for mine workers, with real-time monitoring and early warning systems in place to mitigate risks effectively. One of the most significant advantages of incorporating IoT in mine planning is the shift towards data-driven decision-making and optimising resource management. The applications of IoT in mine planning are diverse and far-reaching, encompassing geological data collection, geospatial analytics, ore movement monitoring and production scheduling.

Historically, mine planners relied heavily on static data and predictive models. These traditional approaches often left room for inaccuracies and assumptions. In contrast, IoT technologies provide mine planners with a wealth of real-time data, offering an accurate and up-to-date representation of the mining site [56]. This real-time data empowers mine planners to make informed decisions based on current conditions. It minimises the reliance on historical data, which may not accurately reflect the present state of the mining site. Additionally, IoT technologies contribute to cost savings by optimising resource allocation and operational efficiency.

4.4. IoT in rock mechanics and geotechnical engineering

Rock mechanics and geotechnical engineering are foundational disciplines in mining, directly impacting the safety, stability, and efficiency of excavation processes. These fields are tasked with understanding and managing the behaviour of rocks and soils in mining environments. Historically, this involved extensive manual data collection and analysis. However, with the advent of the IoT, rock mechanics and geotechnical engineering have been reengineered. IoT technologies now play a pivotal role in real-time monitoring, accident prevention, and the optimisation of excavation techniques. This section looks deeply into the significant impact of IoT in rock mechanics and geotechnical engineering, exploring key applications and the various benefits it offers to the mining industry.

4.4.1. IoT applications in rock mechanics and geotechnical engineering

4.4.1.1. Instrumented bolts and supports. Instrumented bolts and rock support systems are crucial components in ensuring the stability and safety of underground excavations. IoT-equipped bolts and supports have the capacity to provide real-time data on rock stress and deformation. This information is vital for assessing the stability of underground excavations and planning reinforcement measures. IoT-enabled bolts are equipped with sensors that continuously monitor the strain and stress on the rock. These sensors can detect subtle changes in the rock's behaviour, providing early warnings of potential instability. The data collected by these instrumented supports is integrated into a centralised system, which allows engineers and geotechnical experts to track changes in rock conditions. This real-time monitoring of rock stress and deformation has modernised rock mechanics [57–60]. It enables engineers to detect critical changes in the structural integrity of the rock and take immediate corrective actions. This is particularly valuable in preventing accidents related to rockfalls and collapses. It also ensures that support systems are only reinforced when necessary, optimising resource utilisation.

4.4.1.2. Geotechnical sensors. Geotechnical sensors play a pivotal role in assessing the stability of underground excavations and monitoring ground movement. IoT technologies have introduced a paradigm shift in geotechnical engineering by enabling continuous and remote monitoring of ground conditions. IoT sensors, embedded in the ground or rock formations, provide real-time data

on ground movement, subsidence, and the stability of underground excavations [57,61]. These sensors detect even the slightest shifts in the earth's structure and promptly transmit this data to a centralised monitoring system. This information is invaluable for assessing the health of underground tunnels, drifts, and stopes. Continuous monitoring of ground movement and stability not only allows for early detection of potential issues but also contributes to efficient resource allocation. Geotechnical engineers can make data-driven decisions about the need for reinforcement measures or adjustments in excavation techniques. This leads to improved safety and resource utilisation.

4.4.1.3. Seismic and vibration monitoring. Seismic activity and ground vibrations are critical parameters in rock mechanics and geotechnical engineering. They can provide early warnings of potential rockfalls, collapses, or underground explosions. IoT sensors have become integral in detecting seismic activity and ground vibrations. IoT-driven seismic and vibration sensors are often strategically placed in underground excavations and near fault zones [62]. These sensors continuously monitor ground movements and vibrations. When unusual seismic activity or ground vibrations are detected, these sensors trigger automatic alerts. These warnings can be sent to both on-site personnel and remote monitoring centres, ensuring that immediate actions can be taken to mitigate risks. The real-time monitoring of seismic activity and ground vibrations contributes to a proactive approach to safety in mining operations. It ensures that workers are not exposed to unforeseen risks and that accident prevention measures can be implemented in a timely manner.

4.4.1.4. Seismic and geophysical monitoring. Understanding the subsurface structures and variations in mineral deposits is essential for accurate rock engineering. To achieve this, continuous monitoring of seismic and geophysical data is paramount. IoT sensors have proven instrumental in this context. IoT-enabled seismic and geophysical sensors are deployed at mining sites to provide real-time data on subsurface conditions [2,63]. These sensors can detect changes in rock density, stress, and seismic activity. The real-time nature of the data enables rock engineers to gain a comprehensive understanding of the subsurface structures, mineralisation patterns, and potential deposit variations. By continuously monitoring seismic and geophysical data, IoT technologies contribute to a dynamic and evolving geotechnical process. Rather than relying solely on static data, rock engineers can adjust their models based on real-time information, reducing the risk of inaccuracies and oversights.

4.4.1.5. Predictive analytics. Predictive analytics, powered by IoT, are transforming the way rock mechanics and geotechnical engineering operate [62,64,65]. These models analyse historical and real-time data to forecast ground stability issues. They provide early warnings and enable proactive measures to mitigate risks. Predictive analytics models are based on machine learning algorithms that consider a multitude of factors, including historical geological data, real-time sensor data, weather conditions, and excavation patterns [32]. By analysing this data, these models can identify patterns and trends that may lead to ground instability. They provide early warnings to geotechnical engineers, allowing for the implementation of reinforcement measures or adjustments to excavation plans. Predictive analytics have proven invaluable in preventing accidents and ensuring the safety of workers. By providing early warnings and proactive recommendations, they significantly reduce the risk of rockfalls, collapses, and other ground instability issues.

4.4.2. Keynote on IoT in rock mechanics and geotechnical engineering

The incorporation of IoT technologies into rock mechanics and geotechnical engineering is instrumental in ensuring the safety, optimised excavation and efficiency of mining operations. IoT has revitalised accident prevention by introducing real-time monitoring and early warning systems, reducing the risk of rockfalls, collapses, and other ground instability issues. It has also optimised resource utilisation by enabling data-driven decisions on excavation methods and

reinforcement measures. The real-time monitoring and early warning systems introduced by IoT significantly reduce the risk of accidents in underground excavations. Continuous monitoring of seismic activity, ground vibrations, and ground movement ensures that workers are not exposed to unforeseen risks. When potential issues are detected, timely actions can be taken to mitigate risks, ultimately ensuring the safety of workers. IoT technologies significantly contribute to cost savings in rock mechanics and geotechnical engineering. By preventing accidents and optimising support systems, IoT reduces the costs associated with accidents and the unnecessary reinforcement of rock structures. This results in substantial cost savings for mining operations.

4.5. IoT in mine ventilation

Mine ventilation is a lifeline for underground operations, maintaining air quality, temperature, and pressure to ensure the safety and well-being of miners. Traditionally, mine ventilation systems were operated manually with limited real-time monitoring capabilities. However, the advent of the IoT has brought a new era for mine ventilation which determines the Ventilation on Demand (VOD) in real-time. IoT technologies have transformed ventilation systems by providing real-time monitoring and control capabilities, ensuring that air quality remains at safe levels, energy consumption is optimised, and miners are protected [66–68]. This section explores the significant impact of IoT in mine ventilation, discussing key applications and the many benefits it offers to the mining industry.

4.5.1. IoT applications in mine ventilation

4.5.1.1. Air quality sensors. Maintaining high air quality is of paramount importance in mining operations, as the underground environment can be laden with harmful gases and particulate matter. IoT sensors equipped with a range of environmental sensors, including those for gas detection and particle monitoring, continuously monitor air quality conditions [34,54,69,70]. These sensors can detect harmful gases such as methane, carbon monoxide, and sulphur dioxide, as well as fine particulate matter. In real time, they transmit this data to a centralised monitoring system, where it is processed and analysed. When hazardous conditions are detected, these sensors trigger automatic responses in the ventilation system to ensure that air quality remains safe for miners. IoT-enabled air quality sensors not only provide a proactive approach to maintaining safe air quality but also significantly reduce the risk of health issues or accidents due to exposure to harmful gases and particulate matter.

4.5.1.2. Energy-efficient ventilation. Ventilation systems in mines are energy-intensive and can contribute substantially to operational costs. IoT technologies have introduced energy-efficient ventilation control systems that optimise fan speed and airflow based on real-time needs. These systems continuously monitor environmental conditions, including the number of miners underground, heat generation from machinery, and air quality parameters. By processing this data, they can dynamically adjust fan speeds and airflow to match the actual ventilation needs. For example, during shifts with fewer miners, the system can reduce airflow, saving energy. Conversely, during busy shifts or in areas with higher heat loads, it can increase ventilation to maintain safe conditions. The result is a significant reduction in energy consumption and operational costs, without compromising safety or air quality.

4.5.1.3. Emergency response. IoT-enabled ventilation systems can be programmed to respond to emergencies rapidly. In the event of fires, gas leaks, or other hazardous conditions, these systems can adjust airflow and direct miners to safe zones. For example, if a fire is detected, the ventilation system can redirect airflow to control the spread of smoke and toxic gases. It can also guide miners to escape routes with clean air, ensuring their safety. This rapid response is invaluable in emergencies, reducing the risk of injuries and fatalities.

4.5.1.4. Compliance monitoring. Compliance with air quality and ventilation standards is a legal requirement in mining [71–73]. Failure to meet these standards can result in fines and regulatory issues. IoT data is essential for compliance reporting, as it provides accurate and comprehensive information about air quality and ventilation conditions. IoT-enabled ventilation systems continuously log data on air quality, airflow rates, temperature, and pressure. This data is securely stored and can be easily accessed for compliance reporting.

4.5.1.5. Safety and environmental monitoring. Safety is a paramount concern in mining, and environmental responsibility is equally important. IoT sensors have found extensive use in monitoring both safety and environmental conditions within mining operations. For workers' safety, real-time monitoring of environmental conditions is crucial. IoT sensors, including air quality sensors, detect harmful gases and particulate matter in real time. These sensors continuously assess the air quality within the mine, ensuring that it remains within safe limits. In cases of hazardous conditions, automatic alerts are generated to notify workers and management, allowing for the immediate evacuation or adjustment of operations to ensure safety. Environmental monitoring extends beyond worker safety and encompasses the broader ecological impact of mining operations. IoT sensors can continuously monitor parameters such as water quality, noise levels, and ground stability [49,69,74,75]. The real-time data collected by these sensors aids mine engineers in assessing and mitigating the environmental impact of mining activities.

4.5.2. Keynote on IoT in mine ventilation

The incorporation of IoT technologies into mine ventilation has ushered in a new era of safety and efficiency in the mining industry. IoT applications, including air quality sensors, energy-efficient ventilation, emergency response, and compliance monitoring, are transforming the way mine ventilation operates. The benefits of IoT in mine ventilation are substantial, encompassing enhanced safety, energy efficiency, and regulatory compliance. IoT technologies protect miners from health risks and accidents by maintaining safe air quality conditions and providing rapid responses in emergencies. They significantly reduce energy consumption and operational costs, contributing to cost savings. Moreover, they ensure that mining operations meet all regulatory standards and prevent compliance issues.

4.6. IoT in fleet and personnel management

Efficient fleet and personnel management are the lifeblood of mining operations. In the dynamic and high-stakes environment of mining, it is crucial to ensure that the right equipment is in the right place at the right time and that the safety and well-being of personnel are upheld. Traditionally, these processes were managed manually or with limited real-time capabilities. However, the advent of the IoT has ushered in a new era for fleet and personnel management in mining. IoT technologies have streamlined these operations by providing real-time tracking, monitoring, and automation capabilities. This section explores the profound impact of IoT in fleet and personnel management, delving into key applications and the different benefits it brings to the mining industry.

4.6.1. IoT applications in fleet and personnel management

4.6.1.1. Asset tracking. Asset tracking is a foundational application of IoT in fleet and personnel management. In mining, where valuable equipment and vehicles are spread across vast and often challenging terrains, IoT sensors play a pivotal role in tracking the location and status of mining assets [25,74,76,77]. These IoT sensors are often integrated with mining equipment and vehicles. They continuously transmit data on their location, operational status, fuel levels, and maintenance needs to a centralised monitoring system. Mine operators and managers can access this real-time information, enabling them to make informed decisions about equipment

allocation and maintenance scheduling. Asset tracking with IoT technology brings significant benefits to mining operations. It ensures that equipment is optimally utilised, minimising downtime and reducing operational costs. It also helps prevent theft or misplacement of valuable assets.

4.6.1.2. Personnel safety. Safety is a principal concern in mining, where miners often work in challenging and hazardous conditions. IoT technologies have introduced a range of applications focused on enhancing personnel safety. Wearable IoT devices, such as smart helmets and vests, have gained prominence in mining. These devices are equipped with sensors that monitor vital signs and the location of miners in real time. For example, they can track a miner's heart rate, body temperature, and oxygen levels. Onifade et al. [42] note that in the event of an emergency, such as a cave-in or gas leak, these devices can trigger alarms and provide the exact location of the affected miner. Personnel safety applications of IoT provide critical advantages. They enhance safety by ensuring that miners' vital signs are continuously monitored, reducing the risk of health issues. In emergencies, they enable rapid response by pinpointing the location of miners, potentially saving lives.

4.6.1.3. Automated maintenance. Predictive maintenance is another key application of IoT in mining. IoT-driven systems monitor the condition of mining equipment and vehicles in real time, automatically scheduling maintenance tasks when needed. This approach significantly reduces downtime and extends the lifespan of equipment. IoT sensors are integrated with various mining equipment components, such as engines, hydraulics, and sensors for temperature and vibration. These sensors continuously transmit data on the condition of these components to a centralised maintenance system. When anomalies or signs of wear and tear are detected, maintenance tasks are automatically scheduled. Automated maintenance systems powered by IoT have a substantial impact on mining operations [4,25,45,49]. They extend the lifespan of equipment, reducing the need for premature replacements. By reducing unplanned downtime, they optimise operational efficiency and lower maintenance costs. By automatically scheduling maintenance tasks when equipment requires them, this approach extends the lifespan of equipment and reduces downtime. It optimises maintenance costs and ensures that equipment is always in good working condition [32].

4.6.1.4. Fleet optimisation. Fleet optimisation is a complex task in mining, involving the management of numerous vehicles and the efficient allocation of resources. IoT data is used to optimise vehicle routes, reduce fuel consumption, and improve fleet productivity. IoT sensors integrated into vehicles collect data on their location, fuel consumption, and performance parameters [31,78]. This data is processed in real time and analysed to identify the most efficient routes and allocate resources optimally. Fleet optimisation with IoT has several benefits for mining operations. It reduces fuel consumption, which is a significant operational cost, and minimises the wear and tear on vehicles. By improving route efficiency and resource allocation, it enhances the productivity of the entire fleet.

4.6.2. Keynote on IoT in fleet and personnel management

The integration of IoT technologies into fleet and personnel management has led to a new era of efficiency and safety in the mining industry. IoT applications, including asset tracking, personnel safety, automated maintenance, and fleet optimisation, are transforming the way these processes operate. The benefits of IoT in fleet and personnel management are substantial, encompassing enhanced safety, operational efficiency, and predictive maintenance. IoT technologies protect miner workers from health risks and accidents, enhance productivity, and reduce operational costs.

4.7. Real-world examples of IoT implementation in the mining industry

Some of the world's leading mining companies which have incorporated IoT in their mining operations are Rio Tinto, Vale, Agnico Eagle Mines, Barrick Gold, Northern Star Resources, BHP, Glencore, Jiangxi Copper, Polymetal International, POSCO, Anglo American, AngloGold Ashanti, Kinross Gold, Newcrest Mining, Nornickel, South 32, Zijin Mining and Saudi Arabian Mining [79]. To maintain the brevity of this paper, the following discussion covers the IoT implementation at BHP, Rio Tinto and Vale as summarised by [79].

4.7.1. BHP

- BHP has implemented the use of autonomous trucks across its various mining operations since year 2017. In the year 2020, amidst the challenges posed by COVID-19, BHP introduced the Dynamics 365 Remote Assist Dash Maintainer Tools. These tools were designed to enable equipment staff to collect critical information and data remotely, thereby ensuring the safety of the workforce. The utilisation of IoT sensors installed on machinery, alongside Microsoft Azure cloud services, represents a significant advancement in remote operational capabilities at BHP.
- BHP has also employed cloud services in conjunction with a mixed-reality headset device, facilitating on-site support for auto electricians and mechanical fitters. In an innovative approach to enhance driver safety, the company has invested in specialised caps capable of logging drivers' brainwave activity. This initiative aims to monitor signs indicative of fatigue or the onset of sleep among drivers, achieved through the integration of sensors within a six-inch strip fitted inside the helmets of employees.
- Continuing its trajectory of technological advancement, in 2022, BHP marked the inauguration of its first autonomous drill at the Spence mine located in Chile, signifying a milestone in mining automation.

4.7.2. Rio Tinto

- In 2015, Rio Tinto inaugurated its journey towards predictive maintenance through the establishment of its Analytics Excellence Centre located in Pune, India. This initiative aims at analysing data procured from a comprehensive array of sensors affixed to both stationary and mobile apparatus within Rio Tinto's operations. The objective is to anticipate and avert engine failures as well as other incidents that could result in operational downtime.
- Moreover, Rio Tinto's Mine Automation System (MAS) consolidates data from approximately 98% of the company's mining locations into a unified data format. This data is subsequently visualised through the Rio Tinto Visualisation (RTVis) platform, which amalgamates information gathered from autonomous machinery produced by various manufacturers.
- In a groundbreaking announcement made in July 2021, Rio Tinto disclosed its plans to introduce the world's inaugural fully autonomous water trucks at its Gudai-Darri iron ore mine located in Western Australia. This endeavour, developed in partnership with Caterpillar, aims to digitally monitor water usage and diminish wastage. The deployment of these dust suppression vehicles came a year subsequent to the mine's official inauguration, earning it the designation of Rio Tinto's most technologically sophisticated iron ore mine within the Pilbara region. The site is distinguished by its use of autonomous trucks, trains, drills, water carts, a comprehensive digital twin, and an assortment of robotic technologies.
- As of 2023, Rio Tinto persists in its commitment to technological advancement, particularly in the enhancement of its autonomous haul trucks. This is achieved through strategic collaborations with entities such as Scania, Wenco, and Caterpillar. The partnership focuses on refining open-pit operations via the implementation of the Cat MineStar Fleet management system, particularly at the Bingham Canyon Mine.

4.7.3. Vale

- In the year 2016, Vale embarked on a digital transformation strategy to align itself with the advancements of Industry 4.0, notably integrating the IoT among other technologies. In a significant move towards enhancing its digital infrastructure, Vale entered into a partnership with Vivo in 2019 to establish a private 4 G-LTE network across Brazil, with an investment close to BRL21 million ($3.7 million). At the heart of its operations in the Carajás and Brucutu mines within Brazil, the company has adopted the use of autonomous haul trucks.
- Vale has also leveraged drone technology to oversee ore transport waggons, aiming to bolster efficiency and safety within the Tubarão railroad yard located in Espírito Santo, Brazil.
- Further extending its technological footprint, Vale has introduced autonomous excavators at its Totten mine in Canada, which are capable of remote operation. The utilisation of IoT solutions by Vale spans a broad spectrum of applications, including but not limited to, vibration monitoring of rollers and conveyor belts, as well as geotechnical instrumentation. By the year 2022, Vale reported the operational integration of 72 pieces of autonomous equipment spread across four states in Brazil, marking a significant milestone in its technological evolution.
- In 2023, Vale continued its trajectory of innovation by endorsing the SpectraFlow Crossbelt Analyzer. This technology facilitates the online measurement of iron ore material, applicable across the company's ports and mining sites, reinforcing Vale's commitment to technological integration within its operational framework.

4.8. Examination of the positive implications and challenges of IoT implementation in the mining industry

As already detailed in this paper, IoT uses span across a broad spectrum of operational, technical, and strategic aspects of the mining sector. This section provides a more detailed examination of the implications, challenges, and future prospects of IoT in the mining industry.

A well-considered adoption of IoT in the mining industry has the following positive implications.

4.8.1. Operational efficiency and productivity

The application of IoT technologies enhances mining operations by automating processes, which leads to increased safety, productivity, and environmental sustainability. Smart machines and sensors enable real-time analysis and optimisation of operations, resulting in reduced downtime and increased output.

4.8.2. Safety and environmental sustainability

IoT contributes significantly to creating a safer working environment by enabling remote monitoring of hazardous areas, predictive maintenance to prevent equipment failure, and real-time tracking of environmental conditions. This not only protects workers but also helps in minimising the environmental impact of mining activities.

4.8.3. Data driven decision making

The extensive data collection and analysis capabilities of IoT systems allow for more informed decision-making across various aspects of mining operations, from mine planning to resource estimation and fleet management. This data-driven approach helps in optimising resources and reducing uncertainties. It can be observed from the study that the implementation of IoT in the mining industry faces the following challenges.

4.8.4. Integration and compatibility issues

A major challenge is integrating IoT technologies with existing systems and ensuring compatibility across different devices and platforms. This requires significant investment in updating legacy systems and ensuring seamless communication between different components of the IoT ecosystem.

4.8.5. Data security and privacy

With the increasing reliance on data, securing this information against cyber threats and ensuring privacy becomes paramount. The mining industry must implement robust cybersecurity measures to protect sensitive operational and personnel data.

4.8.6. Workforce upskilling

The shift towards more technologically advanced operations necessitates upskilling the workforce. Employees need training to adapt to new tools and technologies, which represents both a logistical and financial challenge for mining companies.

4.8.7. Harsh and remote operational environments

The extreme conditions common in mining locations pose a significant challenge to the deployment and maintenance of IoT devices. Ensuring the durability and reliability of these technologies in such conditions is crucial.

5. Limitations of using IoT in the mining industry

Without a question, IoT is in an evolutionary stage, and the mining sector is ready to incorporate cutting-edge technologies to enhance mining operations. The mining industry is currently dealing with several technical challenges. There is no contact between the processes because the data gathered at the end of each step is shared with the next process in an MS Excel sheet. Several difficulties are described below to enable automatic interaction between these systems. Every mining company must, however, contend with a number of IoT-related issues, including data gathering, unnecessary expenses, and mining safety, in addition to its many advantages and potential. Figure 6 presents a graphical representation of the challenges associated with the implementing IoT, in essence, it underscores the complexities of integrating IoT within the mining sector.

5.1. Difficulty of connecting in a wireless communication network

A company must overcome operational difficulties in order to instal an IoT-based solution. Mining companies frequently need to conduct operations at various remote places, which could be problematic, particularly if more information about the activity is lacking. This turns out to be too expensive for the company and also puts workers at risk.

Even though IoT offers reliable wireless networks in mines, doing so is still difficult unless fibre-optic cables are used. To begin with, there can be gaps in the network's coverage or inconsistent data performance across the board. Data dependability in mining operations is hampered by communication problems, which can occasionally lead to the entire shutdown of IoT applications. On critical projects that require complete data accuracy and also don't increase extra costs, this communication gap caused by the network seems more difficult.

5.2. Various perspectives on IoT adoption in the mining industry

Even though all mining companies are increasingly relying on IoT since it is the present and the future of mining operations, there are two sides to every story. There is disagreement among mining companies on the use of the IoT, and they are still cautious to replace the conventional mining techniques. On the one hand, more industry data demonstrates the

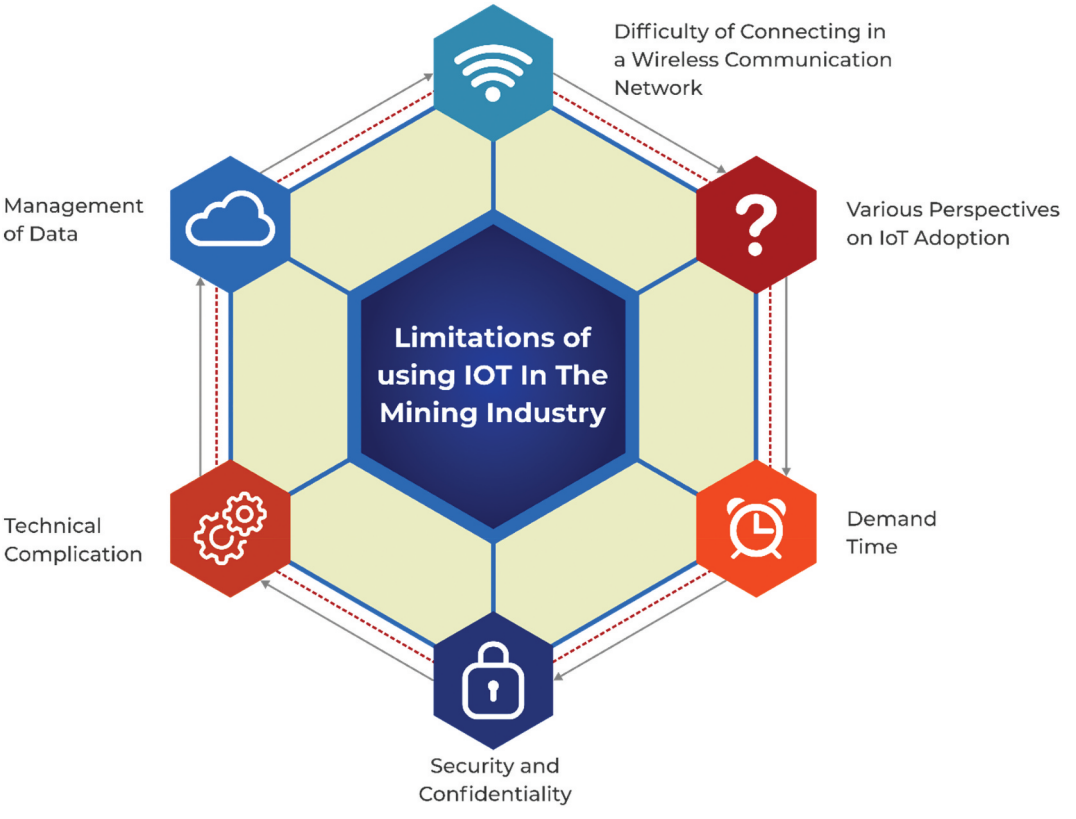


Figure 6. Use case study (mine surveying, mineral resource estimation and mine planning).

beneficial effects of IoT in the mining sector. The mining sector has been growing at a fairly healthy rate, and more and more businesses are implementing IoT solutions to boost operational effectiveness. Leaders in the mining business hold a different perspective. They oppose investing in IoT due to the uncertain business conditions and ongoing market volatility.

5.3. Demand time

The IIoT requires a significant time commitment as well as financial commitment. Numerous devices must be ordered, configured, installed, and integrated into a network by the staff, who must also make support calls to the manufacturer for assistance. Businesses can swiftly recover their investment if they all move into one location.

5.4. Security and confidentiality

As IoT devices develop and become more prevalent, it is increasingly difficult to keep the data they collect and transmit securely. Cybersecurity is crucial, and mining companies place a high importance on it. The approach doesn't always consider IoT devices. These devices need to be secured against online attacks, hardware-based attacks and physical interference. IoT devices are employed in more sensitive areas like finance and healthcare, therefore data privacy is a major worry for mining companies.

5.5. Technical complication

There is currently no agreement on the standards and procedures for the IIoT, therefore the devices made by various manufacturers may or may not be compatible with the technologies already in use. It is challenging to implement each type effectively since they each require a particular hardware connection and configuration.

Even though IoT devices appear to be doing simple activities like counting swipes at a safe door, their creation involves a number of intricate technologies. They may have a detrimental impact on everything connected to it if they are giving crucial data to another workflow or system.

Most devices require ongoing electricity or internet access to operate properly. When one of them fails, the entire system and everything connected to it also fails. These gadgets are crucial in today's world, and if they fail, many operations would be stopped.

Industries may undergo a transfiguration with the adoption of IIoT, yet the increased connectivity may raise security concerns. Businesses that use operational technologies are aware of how crucial worker safety and product quality are. However, there are a number of issues with availability, scalability, and security as a result of the integration of operations, the internet, automation, and smart equipment.

Since availability and scalability are essential to operation and can be quickly integrated into an IIoT system, the majority of sectors are adept at controlling them. Security is where most businesses fall short. Many companies still use outdated systems and procedures, and end-to-end security and integration might become more challenging with new technology.

Integrating industrial operations and IT safely is another difficulty with IIoT implementation. User data must comply with international privacy laws. A corporation must collect data in order to generate key insights, but personal information must be kept separate and kept in secured systems. Storing personal information alongside corporate information carries significant exposure risks.

5.6. Management of data

IoT devices capture data, which is then stored in a central data layer where it may subsequently be retrieved for analysis. Data management is an important component since it provides a picture of all processes carried out within the organisation and tracks how one process affects another [4]. This enables the organisation to decide on the best course of action for its operations and business. Various sources, including manufacturing execution systems (MES), enterprise resource planning (ERP), etc., collect and store data. This causes data management to become more difficult, which is addressed by a number of strategies including migration, and replication.

6. The challenges and complexities of implementing IoT in the mining industry

The application of the IoT in the mining industry promises transformative benefits, from increased safety to enhanced efficiency and sustainability. However, like any technological innovation, the adoption of IoT in mining is not without its challenges and complexities. In this comprehensive exploration, we delve into the various challenges faced by the mining industry in implementing IoT technologies. From the unique environmental constraints of mining operations to data security and the need for workforce upskilling, we dissect the key challenges and provide insights into potential solutions.

Figure 7 presents a structured, circular flow diagram that visually represents the challenges and complexities of implementing IoT in the mining industry. The diagram further categorises the challenges and showcases their interrelations. Each segment of the outermost wheel represents one of the 11 challenges discussed in Section 6. The innermost band contains icons that symbolise the

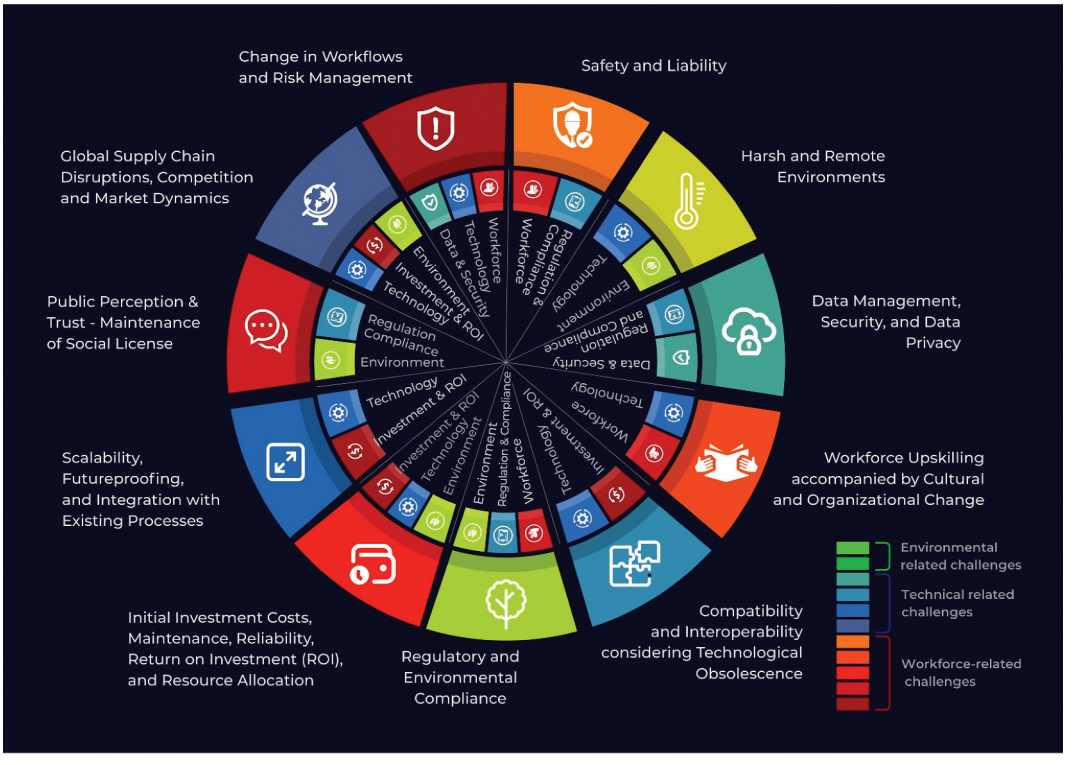


Figure 7. Challenges and complexities of using IOT in the mining industry.

overarching themes areas of these challenges, the six thematic areas are e*nvironment, workforce, technology, data and security, investment and ROI, regulation and compliance*. The connection of the inner band to the outer band shows how a group of thematic areas influences or is related to the specific challenges of implementing IoT in mining. By illustrating these connections, the diagram becomes a dynamic tool for understanding the complexities and interrelated nature of the challenges associated with implementing IoT in the mining industry.

6.1. Safety and liability

The integration of IoT in mining must prioritise worker safety. This includes ensuring that IoT systems do not introduce new safety risks. Conduct thorough safety assessments for IoT implementations. Implement systems for emergency response and worker monitoring to enhance safety.

6.2. Harsh and remote environments

One of the foremost challenges in implementing IoT in mining is the extreme and often unpredictable environmental conditions in which mining operations occur. Mines are located in diverse regions, from scorching deserts to frigid arctic landscapes. This presents a significant challenge for the deployment of IoT sensors and devices. Extreme temperatures can affect the performance and longevity of hardware, making it necessary to use specialised equipment capable of withstanding such conditions. A potential solution would be to use ruggedised IoT devices that are specifically designed for harsh environments. These devices

are engineered to operate in extreme temperatures, resist corrosion, and withstand physical stresses.

Many mining operations are situated in remote locations where internet connectivity is limited or non-existent. This lack of connectivity can hinder the real-time data transmission that is crucial for IoT applications. As a solution, employ low-power, wide-area network (LPWAN) technologies like StarLink, LoRaWAN or satellite communication systems. These technologies enable IoT devices to communicate over long distances without relying on traditional internet connectivity. Mines are inherently dusty and dirty environments. Dust and debris can clog sensors and damage electronic components, leading to equipment malfunction and data inaccuracies. An essential solution would be regular maintenance and cleaning of IoT devices. Additionally, consider the use of protective enclosures and seals to shield devices from dust and debris.

6.3. Data management, security and data privacy

The deployment of IoT sensors generates vast amounts of data. While this data is valuable, mining companies may struggle to manage and analyse it effectively. Extracting meaningful insights from this deluge of information can be challenging. To mitigate this challenge, implement data management systems and analytics tools that can process and analyse data in real time. These systems should also have the capability to filter and prioritise data, ensuring that only relevant information is acted upon.

Data security is a paramount concern in the mining industry, where proprietary and sensitive information is at stake. IoT devices are potential entry points for cyberattacks, putting the integrity and confidentiality of data at risk. To solve this, employ robust security measures, including encryption protocols, intrusion detection systems, and regular security audits. Additionally, consider implementing blockchain technology for secure data storage and access control.

Mining operations involve the collection of data from employees and contractors. Ensuring data privacy and compliance with data protection regulations is essential. Develop robust data privacy policies and procedures. Implement consent mechanisms and secure data storage and transmission. The use of IoT for mining operations can raise ethical questions related to data privacy, environmental impact, and labour practices. Develop ethical guidelines and consider the ethical implications of IoT implementations. Engage with ethical experts and stakeholders to address concerns.

6.4. Workforce upskilling accompanied by cultural and organisational change

Integrating IoT into mining operations necessitates a skilled workforce capable of operating, maintaining, and troubleshooting IoT devices. Many mining companies may face skill gaps, as traditional mining roles may not encompass IoT-related expertise. Invest in workforce development and training programmes to upskill employees as a solution. Collaborate with educational institutions to develop specialised courses in IoT for mining professionals. IoT implementation may require a cultural shift within mining organisations. Employees must embrace new technologies and data-driven decision-making. Develop a change management strategy that includes communication, training, and incentives to encourage cultural change.

6.5. Compatibility and interoperability considering technological obsolescence

Mining operations often use a mix of legacy and new systems, which may not be compatible or interoperable with IoT technologies. This can lead to data silos and hinder the integration of IoT into existing workflows. To alleviate this challenge, implement IoT platforms that offer application program interfaces (APIs) to facilitate integration with diverse systems. A gradual transition,

starting with pilot projects, can also help to ensure compatibility. IoT technologies are rapidly evolving. This can lead to concerns about investing in technologies that may become obsolete in a short time. Stay informed about technological advancements and consider long-term compatibility and upgradability when implementing IoT solutions.

6.6. Regulatory and environmental compliance

Mining operations are subject to a web of local, national, and international regulations, particularly concerning environmental impact and worker safety. IoT implementation must align with these regulations. Collaborate with regulatory bodies and organisations to ensure that IoT implementations are compliant with existing regulations. Develop clear protocols for data collection and reporting to demonstrate adherence to environmental and safety standards.

While IoT can enhance efficiency, there may be concerns about the environmental impact of increased mining activity. Mitigate these concerns by using IoT for sustainable mining practices. Implement monitoring systems that track environmental indicators and ensure compliance with sustainability goals.

6.7. Initial investment costs, maintenance, reliability, Return on Investment (ROI) and resource allocation

The initial investment required for implementing IoT in mining can be substantial. This includes the cost of IoT devices, infrastructure, software, and workforce training. Consider long-term benefits and ROI. The efficiency gains, cost savings, and safety improvements enabled by IoT can often justify the initial expenditure. IoT devices require maintenance to ensure they operate optimally. In remote and harsh mining environments, maintenance can be challenging and costly. Develop comprehensive maintenance protocols and schedules. Consider predictive maintenance strategies that use IoT data to anticipate equipment issues. Mining companies often require a clear demonstration of ROI before committing to IoT investments. Proving the financial benefits can be a challenge. Develop detailed ROI models that take into account efficiency gains, cost reductions, safety improvements, and other tangible benefits. Provide regular reports to illustrate the realised ROI. Limited resources may pose challenges in implementing IoT technologies, including financial and human resources. Carefully prioritise IoT projects and allocate resources strategically. Start with smaller, manageable initiatives and scale up as resources become available.

6.8. Scalability, futureproofing, and integration with existing processes

As mining operations expand, the scalability of IoT implementations can become a challenge. Ensuring that IoT systems can grow with the business is vital. Prioritise scalability in the selection of IoT platforms and systems. Regularly assess and upgrade IoT infrastructure to accommodate expansion. Integrating IoT into existing mining processes may require significant changes and adjustments. Resistance to change and process disruption can be obstacles. Focus on change management and engage employees in the transition process. Clearly communicate the benefits of IoT to gain buy-in from the workforce.

6.9. Public perception and trust - maintenance of social license

Mining companies may face public scrutiny and challenges in building trust with local communities and stakeholders when implementing IoT technologies. Implement transparency and community engagement programmes. Clearly communicate the benefits of IoT for safety, environmental impact, and community well-being. Mining companies rely on public approval

to operate. IoT implementations must consider the impact on social licence. Engage in community outreach and corporate social responsibility initiatives to maintain and enhance social licence. Ensure that IoT implementations align with community values and expectations.

6.10. Global supply chain disruptions, competition and market dynamics

Global supply chain disruptions, such as those seen during the COVID-19 pandemic, can affect the availability of IoT hardware and components. Diversify suppliers and maintain strategic stockpiles of critical components. Develop supply chain risk management strategies. The mining industry is highly competitive, and the adoption of IoT technologies can be driven by the need to stay competitive. Stay informed about industry trends and competitor actions. Implement IoT strategically to gain a competitive edge.

6.11. Change in workflows and risk management

Adopting IoT technologies may necessitate changes in established workflows and processes, leading to resistance and disruption. Involve employees in the design and adaptation of new workflows and provide training and support. IoT implementations can introduce new risks, including cyber risks and operational disruptions. Conduct thorough risk assessments and develop risk management plans for IoT projects. Address potential risks proactively.

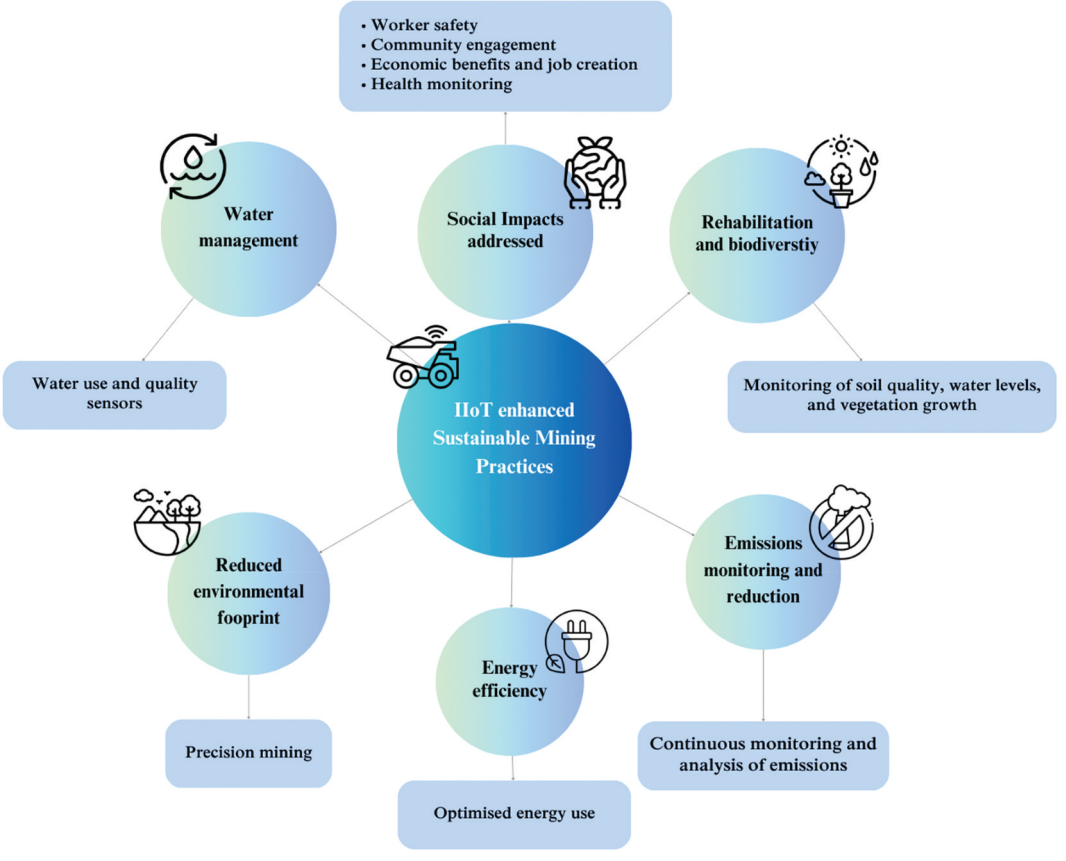


Figure 8. Some of the positive contributions of IIoT to sustainable mining practices.

7. IIoT enhanced sustainable mining practices: consideration of environmental and social impacts

The integration of IIoT in the mining industry has profound environmental and social implications, contributing significantly to the advancement of sustainable mining practices. IIoT technologies facilitate more efficient resource use, reduce environmental degradation, and improve social outcomes within mining communities [80,81]. Figure 8 presents some of the positive contributions of IIoT to sustainable mining practices.

IIoT technologies enable precision mining, which optimises the extraction process and minimises the removal of excess rock and soil. This precision reduces the environmental footprint of mining operations by limiting land disturbance and decreasing waste. IIoT applications in mining help to optimise energy use, leading to significant energy savings. For example, IIoT-driven predictive maintenance ensures machinery operates at peak efficiency, and reducing energy consumption [80]. Additionally, smart ventilation systems adjust airflow in real-time based on the presence of workers and machinery, minimising energy waste. IIoT technologies play a critical role in water conservation and management, a significant concern in mining operations. Sensors can monitor water levels, quality, and flow rates in real-time, enabling the reuse and recycling of water within mining processes and reducing the pollution of nearby water bodies. IIoT systems can continuously monitor and analyse emissions from mining operations, including greenhouse gases and particulate matter [43]. This data allows for the implementation of targeted measures to reduce emissions, contributing to efforts to combat climate change. Post-mining land rehabilitation benefits from IIoT through the monitoring of soil quality, water levels, and vegetation growth, ensuring that restored areas meet environmental standards and support biodiversity.

One of the most immediate social impacts of IIoT in mining is the improvement in worker safety. Wearable sensors monitor workers' health indicators and environmental conditions, alerting them to potential hazards. Autonomous vehicles and machinery reduce the need for human presence in dangerous areas, further enhancing safety [22]. IIoT enables better data sharing and transparency with local communities affected by mining operations. Real-time monitoring of environmental conditions, such as air and water quality, can be shared with the public, building trust and facilitating community engagement. While IIoT can lead to job displacement due to automation, it also creates new opportunities in tech-driven roles. Training and upskilling programmes can help transition workers into these new positions, contributing to economic development within mining communities.

8. Identified research gaps and future prospects of IoT in the mineral industry

With the aid of IoT devices, mines have evolved into the future and become safer. By integrating IoT into mining systems, mining systems have become more reliable and efficient, which has increased output rates and revenues made by mining companies. IoT is still climbing the ladder one step at a time by moving into the future. IoT in mining faces some challenges, but it has fundamentally influenced the industry from what it was in the past.

The IoT is a very disruptive technology because it is accessible and makes use of cutting-edge sensor technologies, big data technology platforms, numerous connectivity networks, edge computing, raw data processing and interactive visualisation, and essential data science [22,81]. Reduced waste, accurate risk and real-time data analysis, and assistance in making well-informed decisions are all benefits of the IoT. The safety of the miners in deep underground mines is another issue that the technology handles. This is one of the most difficult components of the mining sector. Workers' security and safety, as well as the absence of even a single theft case, are guaranteed by real-time tracking and visualisation. Other benefits of using the IoT in mining include fuel utilisation based on raw data and predictive analysis of equipment failure and landslides.

The existing literature on IIoT in the mining industry, as reflected upon in this paper, provides a comprehensive overview of the applications, benefits, challenges, and future prospects of IIoT technologies in enhancing mining operations [42,43,80,81]. Through a critical analysis, the study has evaluated the strengths and weaknesses of the literature, assessed limitations, gaps, and inconsistencies, and has highlighted areas requiring further research.

The literature successfully identifies emerging trends and future opportunities in the mining industry, facilitated by IIoT technologies. This foresight is crucial for guiding research, development, and investment in the sector. Certain areas within IIoT applications in mining, such as the impact on the supply chain, the integration with renewable energy sources, and the role of IIoT in supporting circular economy principles in mining, are not extensively covered. These areas offer significant potential for enhancing the sustainability and efficiency of mining operations. There is a noticeable shortage of quantitative data demonstrating the ROI, productivity gains, and safety improvements attributed to IIoT implementations in mining. Quantitative analyses would strengthen the argument for IIoT investment and provide benchmarks for measuring success.

While the existing literature provides a solid foundation for understanding the implications of IIoT in mining, there are significant gaps and areas that require further investigation. Addressing these gaps will not only enhance the understanding of IIoT's potential but also provide practical guidance for its implementation, ensuring that the mining industry can fully leverage the benefits of these technologies.

8.1. Noted gaps and inconsistencies in the literature

8.1.1. Technology adoption models

The literature lacks a detailed discussion on the models and frameworks for adopting IIoT technologies in mining, particularly in regions with limited technological infrastructure. Exploring these models would address a critical gap in guiding mining companies through the adoption process.

8.1.2. Regulatory and policy analysis

There is insufficient examination of the regulatory, legal, and policy challenges associated with deploying IIoT in mining. This includes data privacy, cross-border data flows, and compliance with international standards, which are crucial for global mining operations.

8.1.3. Socio-economic impacts

The literature does not adequately address the socio-economic impacts of IIoT on mining communities, including job displacement due to automation and the skills gap in the workforce. Further research is needed to develop strategies for mitigating negative impacts and fostering community engagement.

8.2. Areas for further research

8.2.1. Integration of renewable energy

Investigating how IIoT can facilitate the integration of renewable energy sources into mining operations would provide valuable insights into making the mining sector more sustainable.

8.2.2. Advanced data analytics

There is a need for research into more advanced data analytics and AI algorithms that can process the vast amounts of data generated by IIoT devices, turning it into actionable insights for decision-making.

8.2.2. Cybersecurity frameworks

Developing specific cybersecurity frameworks and best practices for the mining industry's IIoT implementations is critical, given the increasing reliance on digital technologies.

8.2.3. Worker engagement and training

Researching effective strategies for worker engagement and training programmes to manage the transition towards more automated, IIoT-driven mining operations is crucial for ensuring a skilled workforce.

8.3. Future prospects of IIoT in the mining industry

8.3.1. Autonomous operations

The future of mining with IIoT looks towards fully autonomous operations, where drones, autonomous vehicles, and remotely operated machinery can perform tasks with minimal human intervention, significantly enhancing safety and efficiency.

8.3.2. Advanced predictive analytics

Leveraging machine learning and AI, future IIoT systems will offer even more advanced predictive analytics, enabling mining companies to foresee and mitigate potential issues before they arise, further optimising operations.

8.3.3. Global supply chain integration

IIoT has the potential to integrate mining operations into a global supply chain network seamlessly, allowing for real-time tracking of resources, improved market responsiveness, and enhanced operational flexibility.

8.3.4. Environmental monitoring and compliance

Future advancements in IIoT will enable more effective monitoring of environmental impacts, facilitating compliance with increasingly stringent global standards and helping to ensure sustainable mining practices.

8.3.5. Innovative business models

The data-driven insights provided by IIoT technologies can pave the way for new business models in the mining industry, such as service-based models or partnerships between mining companies and technology providers, leading to shared risks and rewards.

9. Proposal of new frameworks, models, and hypotheses based on the study findings

Based on the comprehensive analysis and findings from the study, there are several innovative approaches and frameworks that can be proposed to enhance the integration of IIoT technologies in mining operations. These frameworks and models aim to address the identified challenges, leverage the innovations discussed, and fill the gaps in current research and practice. Each of the proposed frameworks, models, or hypotheses introduces an innovative approach to integrating IIoT in mining, addressing the critical areas of environmental sustainability, social responsibility, operational efficiency, and resilience against the challenges of mining environments. The mining industry can move towards more sustainable, efficient, and socially responsible operations, leveraging the full potential of IIoT technologies by adopting the proposals.

9.1. Sustainable Integration Model for IIoT in Mining (SIMM)

This is meant to provide a comprehensive guide for integrating IIoT technologies in mining operations that balances operational efficiency, environmental sustainability, and social responsibility. The model is made up of the following components.

9.1.1. Technology adoption pathway

A phased approach for adopting IIoT technologies, starting from pilot projects to full-scale deployment, with milestones for assessing technological compatibility, workforce readiness, and environmental impact.

9.1.2. Data-driven decision-making framework

Leveraging big data analytics and artificial intelligence to process and analyse data from IIoT devices for informed decision-making, predictive maintenance, and real-time monitoring of environmental and safety parameters.

9.1.3. Workforce transition and upskilling programme

A structured programme for workforce development, focusing on upskilling employees to work alongside advanced IIoT technologies and ensuring a smooth transition to more automated and data-driven mining operations.

9.2. IIoT-enabled Environmental Monitoring and Compliance System (IEMCS)

The objective is to develop a system dedicated to continuous environmental monitoring and regulatory compliance, utilising IIoT technologies for real-time data collection and analysis. The components are as follows.

9.2.1. Sensor network for environmental data

Deployment of a wide network of environmental sensors across mining operations to monitor air and water quality, noise levels, and biodiversity impacts in real-time.

9.2.2. Compliance dashboard

A centralised dashboard that aggregates environmental data, benchmarks it against regulatory standards, and provides actionable insights for maintaining compliance and minimising environmental impacts.

9.2.3. Community engagement portal

An online platform that shares real-time environmental monitoring data with local communities and stakeholders, fostering transparency and community engagement.

9.3. Resilient IIoT Architecture for Mining (RIAM)

The goal is to design a resilient and scalable IIoT architecture that ensures reliable operation under the harsh conditions of mining environments and facilitates seamless integration with existing mining technologies. The architecture comprises of the following.

9.3.1. Ruggedised IIoT devices and connectivity solutions

Specification of standards for IIoT devices that are capable of operating in extreme conditions, alongside the deployment of robust connectivity solutions such as LPWAN or satellite communications for remote locations.

9.3.2. Modular and scalable architecture

An architecture that allows for modular integration of new IIoT technologies and scalability to accommodate the expansion of mining operations or the inclusion of new operational areas.

9.3.3. Cybersecurity and data privacy framework

Comprehensive cybersecurity protocols and data privacy measures that protect sensitive operational and personnel data, addressing potential threats and ensuring regulatory compliance.

9.4. IIoT-driven Circular Economy Model for Mining (ICEM)

The objective is to promote sustainable mining practices by integrating IIoT technologies within a circular economy model, focusing on the reduction of waste, the recycling of resources, and the regeneration of natural systems. The components of the model are as follows.

9.4.1. Resource optimisation and waste reduction

Utilisation of IIoT technologies for precision mining to optimise resource extraction and significantly reduce waste production.

9.4.2. Material tracking and recycling system

Implementation of a tracking system for materials throughout the mining lifecycle, from extraction to processing, enabling the identification and recycling of materials where possible.

9.4.3. Regeneration and rehabilitation monitoring

Deployment of IIoT technologies to monitor and support the regeneration of mined areas, ensuring successful rehabilitation and the restoration of ecosystems.

10. Discussion and concluding remarks

The advent of IoT has greatly advanced the mining industry which is labour-intensive and costly to construct due to the large-sized structures. Hence, the indicating that IoT implementation costs in this industry are significant. To obtain raw minerals, mining involves a number of procedures and techniques. IoT-enabled mines, also known as smart mines, are the mining industry's future and are now in use on a global scale because of their many advantages. Because mining is a risky industry worldwide, smart mines have increased workers' safety by using GPS, automation and remote operation to precisely track the entire mine operations.

Through the IoT, physical objects that include electronics, internet connectivity, and other types of technology are linked to one another online. While being monitored and controlled from a distance, these technologies are capable of interaction and communication. The IIoT is an expansion of this in the mining sector to include the large machinery, trucks, tools, and gadgets utilised all over a mine site. These machinery, equipment, and vehicles are connected enabling sophisticated data transmission and analysis. Software at the mine site receives this information and uses it to provide a clear real-time image of the complete mining operation. With the use of these insights, sites can optimise and even automate a number of their procedures and tasks.

From worker and equipment safety, to truck monitoring and tracking, to machine learning and robotics, IIoT may be employed throughout the mining value chain. Mines can convert expensive, risky, or laborious procedures into digital ones that are carried out remotely and in real-time via a variety of sensors or devices. This improves the profitability, sustainability, safety, and efficiency of operations.

IIoT can enhance AI systems to understand and recognise any modifications or problems that need to be fixed, and in some situations, they may even be able to do so on their own without the assistance of a person. When presented with a high-pressure circumstance, such as an emergency, IIoT can eliminate the aspect of human hesitation or error by making an enhanced and quick judgement based on all of the facts. For instance, sensors on equipment around the mine site might be used to monitor mine ventilation and toxicity levels, and then the levels could be automatically adjusted back to acceptable levels without endangering human life. If that fails, it can anticipate and notify errors, improving efficiency and safety.

By establishing real-time connections between people, equipment, business processes, and the environment, the IoT has significantly influenced numerous industries of which mining is not an exception. Some of the IoT apps that have revamped the mining industry include position and proximity sensors, VOD systems, vehicle management and tracking capabilities and autonomous mining equipment. Because of how much IoT technology is used in the mining industry, it can be said that the current mining industry is far more advanced than the traditional one. IoT uses a number of cutting-edge gadgets in an economical manner to boost the performance of the sector as a whole. This includes cutting-edge wearables and sensors that produce a significant amount of raw and real-time data that is processed in real-time and converted into advice for equipment operators.

The IoT in the mining sector demonstrates exceptional efficiency, which is a huge benefit for workers who previously relied on conventional gimmicks. The most efficient way to address all of these problems is via IoT technology, which also provides pertinent solutions. Mining operators will have a better grasp of their site, resources, and operations as a result of implementing automation and digital technologies. Some of the advantages of IoT in the mining industry include lowering uncertainty, streamlining processes, foreseeing problems, boosting safety, managing mining costs, increasing production, and eventually generating profits.

The implementation of the IoT in the mining industry has brought forth a wave of transformative opportunities across various domains, from mine planning to mineral resource estimation, rock mechanics, mine ventilation, fleet and personnel management, and mine surveying. These applications promise substantial improvements in efficiency, safety, and sustainability. However, this comprehensive analysis has revealed that realising the full potential of IoT in mining is not without its multifaceted manifold challenges. This conclusion distils the key takeaways and offers insights into addressing these challenges.

10.1. IOT application in the mine value chain

IoT technologies provide mine planners with real-time data on geological conditions, ore movement, and environmental factors. This real-time data has the potential to reform mine planning by enabling more informed decision-making, reducing operational inefficiencies, and enhancing safety. The integration of IoT in mine planning faces obstacles such as extreme environmental conditions, data overload, and initial investment costs. The extreme temperatures and harsh conditions in mining environments necessitate specialised, ruggedised IoT equipment when installed in the mine plant.

Moreover, the immense volume of data generated by IoT devices can lead to data overload. The initial costs of IoT implementation can be substantial, requiring mining companies to carefully weigh the long-term benefits against the upfront investment. To overcome these challenges, mining companies should invest in ruggedised IoT equipment designed to withstand harsh environments. Data management systems and analytics tools should be implemented to process and prioritise data effectively. Companies should consider the long-term benefits of IoT in terms of cost savings, efficiency gains, and safety improvements to justify the initial costs.

Mineral resource estimation, a fundamental aspect of mining, benefits from IoT through automated drilling and sampling, geophysical monitoring, remote sensing, and comprehensive

data integration. IoT can significantly enhance the accuracy of resource models and reduce estimation errors. Challenges in implementing IoT in mineral resource estimation include the potential data overload, data security concerns, and the need for scalability. The volume of data generated by automated drilling and geophysical monitoring can be overwhelming. Data security is crucial, as IoT devices are potential entry points for cyberattacks. Additionally, ensuring the scalability of IoT systems as mining operations expand is a concern. To address these challenges, mining companies should employ data management systems that can process and analyse data efficiently. Robust security measures, including encryption and intrusion detection systems, should be implemented to safeguard data. Ensuring the scalability of IoT systems requires careful planning and consideration of future expansion.

The application of IoT in rock mechanics and geotechnical engineering is essential for assessing rock stability, monitoring ground movement, and predicting seismic activity. IoT-equipped bolts and sensors play a critical role in ensuring the safety and stability of mining operations. Challenges related to IoT in rock mechanics and geotechnical engineering include extreme environmental conditions, device maintenance, and concerns about safety. The extreme conditions in mining environments require specialised, rugged IoT devices. Regular maintenance and cleaning are essential to prevent sensor malfunction. The implementation of IoT in this domain should prioritise worker safety to prevent accidents and ensure safe working conditions. They should also establish comprehensive maintenance protocols and schedules to ensure the reliability of IoT equipment. Ensuring safety is a top priority, and predictive maintenance strategies can help anticipate equipment issues and reduce risks.

IoT technologies play a crucial role in maintaining air quality, temperature, and pressure in underground mining environments. Air quality sensors, energy-efficient ventilation, and emergency response systems are key applications. Challenges in implementing IoT in mine ventilation include the need for low-power, wide-area network technologies, potential cyber risks, and concerns about energy efficiency. Many mining operations are located in remote areas with limited connectivity, necessitating the use of specialised network technologies. IoT devices are potential entry points for cyberattacks. Balancing energy-efficient ventilation with safety and air quality standards can be complex. Employing low-power, wide-area network technologies and satellite communication can address connectivity challenges. Robust security measures and regular security audits are crucial to protect against cyber risks. Balancing energy-efficient ventilation with safety can be achieved through the use of IoT-driven control systems that optimise fan speed and airflow.

Efficient management of mining fleets and personnel is essential for optimising mining operations. IoT plays a crucial role in asset tracking, personnel safety, automated maintenance, and fleet optimisation. Challenges in implementing IoT in fleet and personnel management include skill gaps, compatibility issues, and concerns about scalability. Ensuring that the workforce is equipped to operate, maintain, and troubleshoot IoT devices is essential. Heterogeneous systems and compatibility issues can hinder the integration of IoT. As mining operations expand, ensuring the scalability of IoT systems is essential. Addressing skill gaps requires investments in workforce development and training programmes. Employing IoT platforms with APIs can facilitate integration with diverse systems. Prioritising scalability and planning for expansion can ensure the long-term viability of IoT systems.

IoT technologies have upgraded mine surveying by enabling 3D mapping, drones and UAVs, real-time data integration, and automated data analysis. These applications enhance precision, reduce surveying time, and cut costs. Challenges in implementing IoT in mine surveying include the need for automated data analysis, precision, and accuracy. Ensuring the reliability of automated data analysis is crucial. Precision and accuracy in surveying are vital for mining operations. The implementation of IoT in mine surveying requires automated data analysis tools that can process data in real-time. Selecting IoT-driven devices that enhance precision and accuracy can help reduce errors in mapping and planning.

While the mining industry stands at the threshold of a transformative era driven by IoT technologies, the journey is not devoid of challenges. The integration of IoT in mine planning, mineral resource estimation, rock mechanics, mine ventilation, fleet and personnel management, and mine surveying necessitates meticulous planning, investment, and a proactive approach to address the unique obstacles of this sector. As a starting point, mining companies should recognise the value of specialised, ruggedised IoT equipment designed to withstand extreme conditions. Investing in data management systems and analytics tools to filter and prioritise data is imperative to manage data overload effectively. Demonstrating the long-term benefits of IoT, in terms of cost savings, efficiency gains, and safety improvements, should be central to justifying the initial investment. Moreover, the challenges surrounding data security, scalability, skill gaps, and integration with existing processes require careful consideration and a tailored approach. Implementing IoT technologies in a manner that prioritises safety, environmental compliance, and social responsibility can foster public trust and enhance social licence to operate. The path towards successfully implementing IoT in the mining industry requires a holistic strategy that encompasses technological, organisational, and cultural aspects. Mining companies should strive to build a culture of innovation and adaptability, encourage workforce upskilling, and engage with local communities and regulatory bodies. With the strategic management of these challenges, the mining industry can unlock the full potential of IoT, ushering in a new era of efficiency, safety, and sustainability, thereby reconfiguring the way mining operations are conducted and reshaping the future of this vital industry.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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