Abstract: The mining industry is by nature a challenging and demanding sector. Beyond ore extraction, management, processing, and transportation are involved in mining activities. Mining operations, often located in geographically remote and isolated areas, are capital-intensive and have substantial environmental and social impacts. The sector is considered mature and conservative regarding innovation. Nevertheless, its multidimensional nature, combined with declining ore grades and the increased demand for scarce resources, generates an imperative for innovation and the adoption of new technologies. In line with Industry 4.0, Mining 4.0 is the framework for integrating technologies such as the Internet of Things (IoT), automated drones, 3D printing, robotics, sensors, data analytics for monitoring, and performance evaluation in the mining industry. The legislation, the regulatory framework, and governance arrangements often create barriers to the adoption of innovative concepts in the mining sector. This study is an overview of gaps, barriers, inefficiencies, and enablers in the regulatory framework of the mining sector in relation to the utilization of new technologies.

Keywords: mining industry; Industry 4.0; Mining 4.0; digital transformation; barriers; policies

1. Introduction

The mining sector refers to a complex of industrial enterprises involved in the extraction of minerals, ores, and other valuable geological resources [1,2]. The mine extraction includes surface or underground mining techniques, mineral processing, extractive metallurgy, and the reclamation of the mine at the end of its life [3]. Mining, being a multi-billion-dollar industry operating worldwide, is a key driver in the economic development of many countries in terms of Gross Domestic Product (GDP) [3]. For example, in Mongolia, in 2018, the mining output values revealed a 28.88% share of national GDP, 16.17% in Congo Dem. Rep., 11.46% in Chile, 8.21% in Peru, and 4.93% in Australia [4]. Beyond raw material recovery and mineral production, a mining operation creates value through employment, income generation, local procurement, tax revenues, enhanced infrastructure, etc. Nonetheless, this sector faces numerous challenges in different aspects. Climate, social, and environmental (ESG) pressures, health and safety issues, geopolitics, innovation and technology changes, labour shortage, operational costs, and productivity challenges are some of them [5–7].

Even though mining companies are not well-known as technological providers, the deployment of new technology solutions can serve the mining sector to overcome its challenges, from ESG to productivity, to ways of lowering costs, declining ore deposits, and difficult geologies [8,9]. The incorporation of automation systems in the minefield, workforce-tracking systems by using wearable technologies, Global Positioning Satellite (GPS) and navigation systems, wireless monitoring systems, operational and artificial intelligence technologies utilizing IoT can improve mining industry performance in different aspects [10,11]. However, to adopt these technologies some existing barriers have
to be surpassed. Such barriers may include disruption of the existing value chains, safety challenges, management of labour transitions, high upfront costs, new or revised standards, regulations, disruption of the existing value chains, political and economic upheaval.

The scope of this study is to review and analyse barriers and issues generated by legislation, regulatory frameworks, and governance arrangements regarding the mining sector. The bureaucracy and the late update of the standards and regulations for a rapid technology development are some of the reasons leading to these issues.

2. Industry 4.0 and Mining 4.0

Mining sector experienced many changes in the past 100 years, especially regarding efficiency and safety. This transformation of the sector has culminated in recent years and is related to Industry 4.0 and technological innovation. Industry 4.0 brings a new concept to the industry. This concept is based on the advanced digitalisation of production processes and the communication of internet-oriented technologies [12]. It allows the cooperation of smart sensors, machines, and information technology systems across the value chain. The main technological innovations in this context are automation, deep digitalization, the IoT, artificial intelligence, and convergent technologies in manufacturing and other industries [13]. In line with Industry 4.0, Mining 4.0 aims for sustainable, safe, and productive operations [14]. Mining 4.0, which is the equivalent of Industry 4.0 in geotechnology development, aims at the integration of unmanned technologies, remote processes control, and digital simulation in the mining industry [15]. Implementing Mining 4.0 technologies can be subject to regulatory, legislative, and policy barriers, which vary depending on the respective authorities in charge each time.

3. Mining Sector Opportunities and Barriers to Technological Innovation

The necessity of transitioning mining into a more innovation-friendly sector for companies to remain competitive is important for ensuring and improving efficiency and productivity, safety, environmental responsibility and sustainability, resource optimization, access to remote deposits, cost competitiveness, global competitiveness, supply chain integration and regulatory compliance. Artificial Intelligence (AI) contributes to the mining industry’s (i) exploration; the process may become more efficient by identifying and analysing potential sites and processes; and (ii) predictive site maintenance, where AI can run numerous different scenarios highlighting potential issues and ensuring the safety and stability on the site. By introducing AI, mining companies have improved their mining throughput by 10–20% and their procurement productivity by up to 50% [16]. Automation improves the operational efficiency and provides remote control for eliminating workers’ exposure to hazardous environments. Drones have access to acquire information from difficult-to-reach areas, providing detailed insights into conditions before operations begin and reducing maintenance costs for damaged machinery. In addition, IoT networks, based on the synergy of wireless technologies and microelectromechanical systems, contribute to the traceability and visibility of the mining operations and can automate data-gathering [17].

Indicatively, Rio Tinto, one of the leading mining corporations in digitalization, uses the mine automation systems to enable different systems to cooperate, and operates a network server for gathering data from 98% of company sites that can be displayed visually. AI is used to generate orebody models, organize the equipment dispatch, and predict and control the blasts. Rio Tinto has also incorporated autonomous tracks that are operated by supervisory systems and central controllers. In 2018, the autonomous trucks operated, on average, 700 h more than conventional haul trucks with 15% lower costs. Furthermore, land rovers are used for checking high walls in open pits and parts inside big machinery, and for sample collecting (e.g., water sampling) for environmental inspections [18–20].

This transformation increases productivity and makes the mining sector more energy-efficient and safe, impacting the environmental and economic performance. However, this action has to be realized in a systematic, structured, and well-organized manner to avoid negative effects on mining operation and society.
The challenges for digital effectiveness and avoiding the most relevant risks in the mining industry require taking action. Two significant categories can be distinguished. The first is focused on cybersecurity, which constitutes a fundamental element in digital transformation [12], and the second one is the adequacy of the current labour competencies. Other obstacles are related to organizational resistance to change, considering that changes are required in organizational structures [21], new safety challenges, disruption of the existing value chains, as well as of the political and economic dynamics [22].

3.1. Cybersecurity Issues and Frameworks

Through the integration of new technologies, the mining industry is moving into the next stage of evolution. The false sense of security, as mining organizations had relied on obsolete securing systems, combined with rapid technological advance in the sector, resulted in data breaches and the loss of intellectual property, risking financial loss, brand sabotage, human safety and health, supply chain disruption, product delivery equipment and environmental damages [23]. In December 2022, the Canadian Copper Mountain Mining Corporation encountered a specific ransomware attack that resulted in disruptions to its operational continuity. The attack compelled the organization to initiate a temporary shutdown of the site mill to assess the integrity of its dedicated control system. Concurrently, several operational processes were transitioned to manual operations as a precautionary measurement [24]. Moreover, in March 2023, Rio Tinto experienced a cybersecurity breach that enabled malicious actors to exfiltrate sensitive data, including employees’ personal information, which was then disseminated on the ‘dark web’ [25]. To overcome this threat, a regulatory arrangement has to be set at the organizational and governmental level.

To close this gap and form a reliable regulatory framework, the key issues have to be recognized and addressed. Regarding the organizational level, indicatively, the regulatory framework needs to define the roles and responsibilities for cybersecurity among information technology functions that are responsible for operational technologies, and third parties that support the organization. Moreover, the critical operational technology assets have to be identified and clearly stated, and the roles and responsibilities of the different teams to be clearly distinguished. The vulnerabilities need to be detected and stated, prioritizing the key assets, and a monitoring system/program must be included [26].

The organizational regulations have to be subject to the national regulations regarding cybersecurity. In the U.S.A., a voluntary framework, providing guidelines and practices to promote the protection of critical infrastructure and cybersecurity-related risks, was released in 2014 [27]. In the European Union, the Cybersecurity Act came into force in 2019 and introduced mandatory cybersecurity requirements [28]. However, there are countries such as Chile, with significant mining activity, where there is no general law that regulates cybersecurity [29]. This differentiation in regulatory framework characteristics and the requirements existing in different countries generate issues for the mining industry security and adoption of new technologies in a unified way in the sector.

3.2. Labour Transition

A mining activity benefits regional development as it increases employment opportunities and boosts the infrastructure facilities in the region. The mining activity can lead to migration in the region and the evolution of the community overall as well. Mining is challenging, especially in terms of employee skills. The lack of new workforce willing to be employed in the mining sector, combined with high retirement rates, and the requirements for new skills for the new technologies entering the mining industry suggests a future shortage is required [7,30]. As a result, the workforce efficiency and the ability for mines to acquire an operation license, in cases the employment rate considering the local community population is one of the conditions, can be affected significantly.
The adoption of new technologies will lead to the reduction of the low- and semi-skilled positions. Queensland, Australia’s coal mining industry projections indicate that the implementation of automation technologies could potentially result in the replacement of roughly 10,000 jobs within the coal mining industry in the foreseeable future. This figure represents approximately 40% of the current workforce engaged in coal mining activities in Queensland [31]. Simultaneously, higher-paying jobs in higher-skilled occupations, such as information technology and engineering, are expected to be increased.

The mining sector is not so attractive due to the difficulties it faces and the geographical restrictions, as the mining sites are mostly in remote regions. It is expected to face increasing competition from other sectors, especially for the younger workforce [32]. Even though this transition involves a dynamic restructuring of the job positions and the skills required, the new jobs created may not be based in mining-affected communities or will not apply to locals who lack the required skills [32].

From this perspective, governments and mining companies have to set new policies for ensuring that labour groups will not be marginalized and be further disadvantaged by the adoption of new technologies. In order to attain this objective, it is essential that mining companies have the capability to systematically record workforce-related data pertinent to their operations. Maintaining a historical record of employment figures for each individual mine site can prove to be a challenging endeavour. Moreover, the prevalence of subcontractors in the mining sector in certain countries further complicates the task of accurately quantifying mining-related employment. While individuals are directly engaged in activities at mining sites, their official employment status may be attributed to entities unrelated to mining. This situation is particularly pronounced in nations like Peru, Mexico, and Chile. Incorporating the information and the impact of new technology transition in the mining sector, governments need to cooperate with companies to a framework that will focus on education policy, skills training, and educational institutions. The collaboration of governments, companies, and institutions will serve for locals to be able to fill the jobs created through this technological transformation of the mining sector [32].

4. Discussion

The mining sector faces numerous challenges. The supply requirements, combined with the difficulties in ore extraction processes due to decreased ore deposits are some of them. In addition, mines have to comply with climate and environmental restrictions, health and safety, and skills shortage. The sector has been considered technologically mature and conservative in innovation. To be able to face many of the challenges mentioned, the mining industry is in a process of technological transformation, incorporating new technological innovations.

In this transformation, new kinds of challenges are generated. To avoid the negative impact of the transition to Mining 4.0 and for that to lead in an improvement of the mining industry, a structured roadmap that will detect and overcome existing barriers must be designed. To achieve this, the mining industry, governments, and even educational institutions need to cooperate and create or/and update the necessary legislation, regulatory, and policies in an international and unified way to avoid the evolution of the mining sector with different speeds. This may serve for creating a concrete base that will facilitate the transition to Industry 5.0 and, respectively, Mining 5.0, regarding the synergy between humans and autonomous machines by collaborative robots, controlling blockchain and management, and postmining [21].

5. Conclusions

This study highlighted some of the risks and barriers the new technological innovations incorporated into the mining sector. Even though a transition is necessary for making the mining sector viable and sustainable, a rapid change without considering the gaps and the barriers generated through this process could lead to undesirable results. Two important barriers have been analysed. Both affect this process and the mining industry overall,
directly or indirectly. To secure the mining operations, structured and complete regulatory considering cybersecurity is required. The second barrier analysed is related to the impact of the technological transformation of the mining sector on local societies. To overcome this challenge and its impacts, new policies have to be created. For a concrete, comprehensive and effective regulatory framework and policy definition, the governmental authorities, the companies’ representatives, and the educational institutions need to participate in this transition.

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