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Working Paper Series

#2026-016

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Published 20 November 2026

DOI: https://www.doi.org/10.53330/RDHK6789

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UNU-MERIT Working Papers
ISSN 1871-9872

Maastricht Economic and social Research Institute on Innovation and Technology
UNU-MERIT

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Global Value Chains in the Era of Industry 4.0 and AI: Extractive Industries in Latin America [*]

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Forthcoming in

Chen L., Estevadeordal A., and Kimura F. (Eds.) (2027). *Emerging Technologies and Global Value Chains in Asia and Latin America.* Jakarta: Economic Research Institute for ASEAN and East Asia (ERIA)

Abstract

Industry 4.0 technologies—digital transformation, automation, artificial intelligence, data analytics, and the Internet of Things—are reshaping extractive industries and their position in Global Value Chains (GVCs), a shift with particular relevance for Latin America's resource-dependent economies. This paper examines the adoption of "Mining 4.0" and AI in Latin American mining, focusing on Chile, and its implications for GVC participation and structure. Drawing on 15 semi-structured interviews with industry stakeholders—from operational staff to C-level executives, suppliers, and public officials—across Chile, Bolivia, Brazil, Colombia, and Peru, we find that technology adoption is progressing unevenly, driven largely by firm size and financial capacity, while smaller firms face persistent barriers. Suppliers, including new entrants from outside the region, are increasingly delivering integrated, data-centric solutions rather than isolated components, signaling emerging opportunities for upgrading within mining GVCs. We conclude with public policy implications, emphasizing skills development, public-private coordination, and targeted support to diffuse Industry 4.0 benefits beyond large operators.

Keywords: Mining Industry; Global Value Chains; Industry 4.0; Artificial Intelligence; Latin America.

J.E.L.: O33, L72, F23.

[*] We wish to thank the editors and José Guilherme Reis for their insightful comments and encouragement. This paper was prepared for the ERIA-Georgetown Americas Institute research project. We gratefully acknowledge ERIA's financial support. Preliminary drafts were presented at ERIA workshop in Jakarta (2025) and IDE-JETRO workshop in Tokyo (2026). We thank participants for their useful comments.

Industry 4.0 technologies—including digital transformation, automation, artificial intelligence, data analytics, the Internet of Things (IoT), and advanced manufacturing—are increasingly central to economic development strategies worldwide. These transformative technologies are reshaping industries, redefining competitive advantages, and offering opportunities for countries to strengthen their participation in regional and Global Value Chains (GVCs). This is also happening in sectors that crucially rely on natural resources and their transformation, such as extractive and mining industries and GVCs, where Artificial Intelligence (AI) and digital technologies are increasingly used. This is especially relevant for Latin American economies, that in many instances rely on extractive industries for their development.

The study will analyze the significance and effects of Industry 4.0 and AI on Global Value Chains in the extractive industries in Latin America and the Caribbean (LAC). The study will explore how digital technologies are being increasingly adopted by the industry, and how they influence efficiency and competitiveness and the organization of industry. It will also explore the main obstacles to its adoption, and the role that public policies could have in this regard.

The mining sector, traditionally characterized by heavy reliance on manual labor, resource extraction, and high capital intensity, is undergoing a profound transformation driven by the Fourth Industrial Revolution, or Industry 4.0. This new paradigm integrates advanced digital technologies—such as the Internet of Things (IoT), Artificial Intelligence (AI), automation, and big data analytics—into industrial processes, creating "smart" systems that are interconnected, data-driven, and increasingly autonomous. The technological shift brought about by Industry 4.0, with digitization and automation, is creating new conditions for future mining production. This is often referred to as *Mining 4.0* (Lööw et al. 2019; Bongaerts 2020).

The emergence of what has been termed Mining 4.0 promises to redefine how resources are extracted, processed, and integrated into global value chains. These technological shifts are not only improving efficiency and safety but are also opening new opportunities for environmental sustainability and social responsibility. As countries and companies seek to meet growing global demand for minerals, especially critical metals required for energy transitions, the ability to modernize operations through Industry 4.0 tools becomes a strategic imperative (Valverde-Carbonell et al., 2024).

Despite its promise, the implementation of Mining 4.0 raises many complex questions. While early adopters, particularly large multinational corporations like Anglo-American, BHP and Rio Tinto, are advancing toward fully automated and digitally integrated mines, other firms and countries face significant barriers to adoption: infrastructure limitations, high costs, regulatory uncertainty, and workforce preparedness. Moreover, beyond the operational level, there is a growing debate about how this technological shift might reshape global value chains. Will mining countries merely remain suppliers of low-complexity commodities, or can they use digital transformation as leverage to enter and upgrade within the value chain?

Recent literature offers valuable insights into these issues. Zhironkina and Zhironkin (2023) provide a comprehensive overview of Mining 4.0 technologies and outline possible trajectories toward Mining 5.0—a future stage emphasizing human-centered design and sustainability. Ulewicz et al. (2022) categorize the opportunities and challenges of digital transformation across economic, environmental,

production, and social dimensions. Ghobakhloo et al. (2023) explore how Industry 4.0 tools can enhance supply chain resilience. Meanwhile, Doamba (2025) discusses how mining affects countries' positions in global value chains, finding mixed outcomes depending on the type of mineral extracted, the extraction model, and the broader institutional and trade context.

This paper aims to build on these contributions and explore the two following research questions:

1. To what extent are Industry 4.0 technologies being adopted in the mining sector in Latin America?
2. What are the implications of this technological transition for countries' participation in global value chains, and for the structure of GVCs?

To answer these questions, we first review the recent literature to discuss what Industry 4.0 is when applied to the mining industry, and which technologies are adopted more extensively. We then present the insights drawn from interviews conducted with high-level professionals and experts working in innovation and technology in the mining sector in LAC. An important aspect of this analysis is the study of the likely influences of Mining 4.0 on the structure and reorganization of GVCs, and on the distribution of value in mining GVCs, identifying opportunities and risks for resource-dependent economies. The paper concludes by outlining implications for public policies.

1. What do we mean by Mining 4.0?

1.1 A mining GVC

A metal mining value chain typically includes a series of activities along various stages (Figure 1). These activities may be carried out by many different firms, based on the relative efficiency of each firm in carrying out a specific task, and the benefits of specializing in that specific task. In some activities, it may prove convenient to vertically integrate different tasks within the same firms. In a value chain, the linkages among different tasks and different firms are especially relevant to the aim of fostering firms' learning, innovation and upgrading, because these relationships often represent flows of knowledge and incentives to improve (Delera et al., 2022, Morrison et al., 2008).

The stages of production (blue boxes – top row) are briefly described with a series of activities (orange boxes – middle row). Linkage opportunities can stem from both the purchase of capital equipment (manufactured goods required for mining operations) and the provision and purchase of mining services; these opportunities require cross-cutting sectoral policies to be fully exploited. Service inputs are required across different activities; green boxes (bottom row) offer some examples of service inputs along the value chain. The *servification* of the mining sector is indeed revealing a greater use of services, that are often outsourced (Korinek, 2020) and have been one of the most significant sources of value-adding in the sector. Mining services that offer the highest rewards are (i) exploration and mining services, and (ii) scientific electronic and other machinery equipment services (Stubrin, 2017; Korinek, 2020). Interestingly, the more sophisticated services' providers are also home to top providers of mining equipment, while none of the largest mining countries is among the top mining services exporters (Korinek, 2020). Several studies highlight how the structure and governance of mining GVCs are typically very hierarchical, with lead firms controlling decisions and technologies and imposing their

standards on intermediate goods and services' suppliers. They are often highly risk-averse – halting mining operations due to a change or failure in technology can cost huge losses – and this leaves little ground for suppliers' experimentation, learning and upgrading (Pietrobelli, Casaburi, Iizuka, 2024, and Pietrobelli et al., 2024).

INSERT FIGURE 1 HERE

1.2 Industry 4.0 technologies and AI in the mining sector

Industry 4.0 technologies and AI are increasingly used in the mining sector. These can be categorized based on their implementation across the key phases of the mining value chain and described as follows (Consejo Minero, 2023):

- **Exploration:** This phase encompasses a series of activities aimed at determining the presence of economically viable mineral resources beneath the surface. Initial exploration efforts focus on identifying geological indicators of mineralization. When preliminary findings are favorable, more advanced techniques, such as geophysical surveys, core sampling, and modeling, are employed to evaluate the extent, geometry, and estimated quantity of the mineral deposits. The overarching objective is to characterize the deposit in terms of both spatial distribution and the concentration of target minerals.
- **Extraction:** This stage focuses on the physical removal of rock material from the mine. It involves a sequence of operations, including drilling, blasting, loading, and hauling of the rock mass. These operations are designed to fragment and transport the ore and waste rock efficiently and safely, forming the foundation for subsequent processing and beneficiation stages.
- **Processing:** The objective of this stage is to separate and concentrate the target mineral from the surrounding gangue material. This is achieved through a series of physical and/or chemical processes, such as comminution, flotation, magnetic separation, or leaching. The ultimate goal is to produce a high-quality concentrate with a high grade of the desired mineral, suitable for further refining or direct use in downstream applications.
- **Commercialization:** Once the final mineral product has been processed and meets the required quality standards, it is prepared for sale and distribution. At this stage, the concentrate or refined material is marketed and sold to manufacturers or other end users for use in industrial processes or the production of finished goods (Banco Interamericano de Desarrollo, 2023).

Some applications of Industry 4.0 technologies to the different layers of the metal mining value chains are described in Figure 2. A wide range of advanced technologies are integrated throughout the mining value chain. In the **exploration** stage, Artificial Intelligence (AI) is increasingly employed for the reinterpretation of geological models, now incorporating a temporal dimension to better understand deposit evolution over time. AI-driven algorithms optimize drill targeting by improving the design of drilling grids, potentially reducing drilling costs by up to 30%. This results in more precise subsurface characterization, offering equivalent or superior resolution compared to traditional methods while

enhancing decision-making in exploration campaigns. In addition, hyperspectral imaging is being used in geological analysis to support mineralogical mapping and geometallurgical modeling, enabling detailed characterization of mineral assemblages and alteration zones with high spatial and spectral resolution.

INSERT FIGURE 2 HERE

In the **extraction** stage, a broad spectrum of technologies is implemented, driven in part by the high-risk nature of these operations. For example, automated equipment is increasingly deployed across mining operations, particularly in drilling, loading, and hauling activities. In the case of autonomous haul trucks, significant productivity gains have been consistently observed. If running a traditional truck requires an average of eleven people, an autonomous haul truck allows substantial reduction in personnel. Moreover, autonomous trucks can go twice faster than manually operated trucks in the mine. However, the transition from manual to automated systems often entails a temporary decline in production, commonly referred to as a "production valley," which can persist for up to three years. These systems require highly controlled and standardized mining conditions to function optimally and need to be trained by human drivers and adapted to the specific circumstances of the mine. This transition period introduces substantial costs, making the short-term economic burden a key challenge in the adoption of automation. An additional example of Industry 4.0 technology is the use of sensors and automated systems to facilitate the real time detection of hard-to-crush materials (Box 1).

BOX 1. REAL-TIME DETECTION OF HARD-TO-CRUSH MATERIALS

A practical example of Industry 4.0 technologies in mining is the real-time detection of hard-to-crush materials. These often originate from extraction processes, including loading, hauling, and underground mine fortification. When these materials reach the crusher, they can cause prolonged downtime and require complex and labor-intensive removal procedures. Real-time detection of such materials is enabled through the integration of Industry 4.0 technologies, including sensors, high-resolution cameras, automated systems, and machine learning algorithms in the extraction process to prevent hard-to-crush materials to damage the crusher.

Source: Authors' own elaboration based on interviews conducted for this study.

Digital twins, or virtual replicas of physical assets and processes, are also used in mining activities. They are built using real-time sensor data to create dynamic models of the mine or of specific operations. These digital representations support advanced analytics, predictive modeling, and real-time visualization, improving decision-making in environments characterized by geological and operational variability. This is particularly valuable in mining, often described as a "factory that is redesigned every week," where short-term optimization of flows of machines, inputs and materials, and layout is critical. Digital twins enhance the accuracy and responsiveness of weekly planning, allowing for near real-time adjustment of operational strategies.[1]

[1] For an example of how digital twins may help operate a mine, see: https://youtu.be/QsNuT9HKMXw?si=GSWNfw3OwIBBrWSF, accessed 10.05.2026.

Real-time data processing, enabled by a robust network of sensors and communication infrastructure, forms the foundation for many of these digital capabilities. The sensorization of equipment and environments provides continuous streams of data on equipment status, environmental conditions, and operational metrics, while high-speed communication networks ensure seamless data integration and transmission.

The Integrated Operations Center (IOC) is another critical component of Industry 4.0 in mining. It serves as a centralized facility that monitors and manages the entire mining value chain—from extraction to port logistics—within a single location. The IOC operates across multiple layers, integrating real-time operational control with strategic planning, thereby maximizing productivity and enabling more responsive, data-driven decisions.

Virtual reality (VR) training represents an innovative application of Industry 4.0 technologies in workforce development. VR allows operators to gain practical experience in immersive, simulated environments, particularly for high-risk or complex tasks. This does not only enhance skill acquisition and knowledge retention but also improves safety by reducing the need for on-site exposure during training.

In the **extraction** phase new technologies are also being developed, and what promises to be the most disruptive one is a chemical extraction technology called lixiviation (Box 2).

BOX 2. CEIBO – LIXIVIATION OF COPPER SULFIDES ORES

CEIBO is a Chilean technology company focused on the development and scaling of innovative solutions for the mining industry. Their primary area of work is the advancement of copper sulfide leaching technologies. Traditionally, the processing of copper ores has followed two well-defined pathways: pyrometallurgy for sulfide ores and hydrometallurgy for oxide ores. CEIBO is pioneering a novel approach that enables the hydrometallurgical treatment of copper sulfides, thereby eliminating the need for concentrator plants and potentially allowing the economic processing of lower-grade ores.

This technology has the potential to significantly increase copper production while representing a major technological leap for the mining industry. It is highly adaptable to the processing of various minerals, offering improved process control, increased efficiency, and recovery rates exceeding 75%. It also enables substantial reductions in water usage, up to five times less compared to conventional methods, and shorter processing cycle times. Moreover, by enhancing the precision and efficiency of resource extraction, it has the potential to extend the operational life of a mine by up to 10 years. To optimize the process, CEIBO integrates advanced data analytics, which plays a critical role in reducing input uncertainty and improving process efficiency. The development relies heavily on a combination of chemical engineering and data science to achieve optimal outcomes.

Despite ongoing efforts across the industry, no commercially viable sulfide leaching technology has yet been successfully implemented at an operational mine scale. CEIBO's work represents a promising step toward overcoming this long-standing challenge in copper extraction.

Source: Authors' own elaboration based on interviews conducted for this study.

In the **commercialization** stage, mining companies have been exploring the implementation of blockchain technologies for over a decade. Sales and trading functions have historically been among the most advanced segments of the mining value chain in terms of Industry 4.0 adoption, characterized by fast and secure digital transactions. Today, these systems are even more efficient, benefiting from improved algorithms and enhanced transaction speeds, further strengthening transparency, traceability, and trust in mineral trading.

In the cross-cutting implementation of Industry 4.0 technologies across the mining value chain, two additional critical areas have emerged: cybersecurity and the digitalization of the processes granting and obtaining permissions. Firstly, the exponential growth in data volume used for operational decision-making has increased the vulnerability of mining operations to cyber threats. As a result, companies have been compelled to strengthen their cybersecurity capabilities, including expanding specialized teams and adopting advanced protective measures to safeguard critical infrastructure and sensitive data.

Secondly, there is a growing need to modernize and digitize the permission granting and regulatory approval processes, which are often seen as bottlenecks in project development. In the case of Chile, the permitting framework for mining projects involves a wide array of authorizations administered by multiple public agencies, including the Environmental Assessment Services (SEA), the National Geology and Mining Service (SERNAGEOMIN), the General Water Directorate (DGA), Regional Health Authorities, Municipal Planning, Ministry of National Assets, among others.

Within this system, several permits exert a disproportionate influence on overall project timelines due to their extensive processing periods. Notable examples include the Environmental Impact Assessment (EIA), which may require up to 29 months of formal review in addition to 12–18 months of baseline environmental data collection; the relocation of water rights administered by the DGA (approximately 20 months); authorizations for major hydraulic works (24–47 months for project approval and 20–36 months for final commissioning); and maritime concessions issued by the Undersecretariat for the Armed Forces (approximately 30 months) (Comisión Nacional de Evaluación y Productividad, 2024).

Other procedures, while shorter in duration, contribute to delays because of their high rejection rates, necessitating multiple application cycles. These include the declaration of national interest by the National Forestry Corporation (CONAF) (10 months) and project approvals for potable water systems (5 months) (Comisión Nacional de Evaluación y Productividad, 2024).

The combined effect of long processing times, repeated submissions, involvement of numerous agencies, and the prevalence of sequential rather than parallel requirements significantly shapes the complexity and duration of the critical permitting path for mining projects. Leveraging technologies such as artificial intelligence and advanced data processing could significantly enhance the efficiency, transparency, and traceability of these procedures—facilitating faster approvals, reducing bureaucratic delays, and aligning with broader digital transformation goals at the national level.

1.3 The possible effects of Mining 4.0 on labor, competences, organization and society

Lund et al. (2024) propose an international scoping literature review of how Mining 4.0 might affect the work environment, competences, organization and society. To our aims, the paper is especially

interesting because it examines publications concerning the exposure of mining companies to concepts such as Industry 4.0 and 5.0, digitalization and automation[2]. The scoping literature review was performed on October 20, 2022, with the academic database Scopus, and examines the likely effects of Mining 4.0 on issues such as the recruitment of skilled workers, the use of digital technology to promote sustainable work environments, and the management of the organizational challenges.

According to the review, the mining industry is facing extensive technological changes with Industry 4.0. The new technologies being developed and implemented in the mining industry are automation, robots, remote control (Holcombe and Kemp 2019) and digitalisation (Young and Rogers 2019). These technological changes are bringing about changes in both mining and work (Holcombe and Kemp 2019).

Technological advancements will have a dramatic impact on work and workplace design (Holcombe and Kemp 2019; Young and Rogers 2019). The search for technological solutions, and the adoption of Industry 4.0 technologies is likely to seek to reduce the physical or cognitive strain for operators, and in general workers' safety. Moreover, the general perception is that there will be a demand for more general skills, such as computer knowhow, creative problem-solving, entrepreneurial thinking and interpersonal skills (Lund et al., 2024), with continuous on-the-job learning.

Although increased safety is desired by all parties involved, there is still not much analysis of the likely changes in work environments that will result from Mining 4.0 (quality of work, attractiveness and job satisfaction are seldom discussed in the literature). In terms of the types of knowledge needed, most of the researchers agree that the mine of the future will require more generic knowledge and skills such as creativity, analytical skills, entrepreneurship, flexibility, independence, responsibility, openness, teamwork and general skills for handling computers and technical equipment (Young and Rogers 2019; Herbert and Hidalgo 2021).

Following the review, the adoption of Mining 4.0 technologies could produce divergent organizational effects, from Mining 4.0 shifting control of production towards mining engineers and metallurgists at the expense of skilled workers, to the workers' positions reinforced with the flattening of organizational structures (Kazancoglu and Ozkan-Ozen 2018). Mining 4.0 may also exacerbate conflicting organizational interests, if the interests of the mining companies in using Mining 4.0 technology to increase productivity and reduce cost-related conflicts with the workers' interest in better working conditions.

2. Methodology

This study adopts a qualitative research approach, drawing on a combination of semi-structured interviews, secondary source analysis, and company website reviews as primary data sources.

[2] The concept of Industry 5.0 is also being discussed beyond the mining industry. Industry 5.0 places greater emphasis on human factors, and the integration between humans and the technological solutions developed during Industry 4.0 (European Commission 2021).

The empirical evidence is based on 15 semi-structured interviews conducted with industry stakeholders. Interview participants were selected based on their relevance mainly to the Chilean mining landscape, with a focus on professionals working in technology and innovation across the sector. Some interviews were also carried out with experts and stakeholders from other Latin American countries such as Bolivia, Brazil, Colombia and Peru to gauge a more complete picture for the region. The selection aimed to capture diverse perspectives, including representatives from small-, medium, and large-scale mining operations, as well as stakeholders across different stages of the mining value chain and Government officials.

The sample included individuals from operational roles to C-level executives, in addition to suppliers and public institutions, ensuring a comprehensive view of the broader mining innovation ecosystem. This multi-stakeholder approach was designed to understand not only the technological adoption across company sizes but also the systemic dynamics influencing digital transformation in the sector.

3. Results and discussion

3.1 The adoption of Industry 4.0 technologies

The following subsection examines the adoption of Industry 4.0 technologies within the mining sector in Latin America, focusing, on the one hand, on the extent to which these technologies have been implemented and, on the other hand, on the underlying motivation, drivers and obstacles shaping their uptake.

3.1.1 Implementation of 4.0 technologies

Secondary sources support the evidence that Industry 4.0 technologies are increasingly implemented across the mining sector (Peña, Ríos, Espinoza, 2024; Zhironkina and Zhironkin 2023). This has been confirmed by our interview findings. However, the extent of technology adoption varies significantly, largely due to the diverse scale of mining operations in LAC, which range from artisanal and small- to large-scale enterprises.

The adoption of Industry 4.0 technologies in **small-scale** mining in Latin America remains limited due to structural, financial, and cultural barriers. In the specific case of one of the interviewees from Chile, operations prior to 2017 relied solely on basic tools such as Excel spreadsheets. Technological integration began progressively, first with the use of cloud-based data storage to improve traceability, and later with the implementation of 3D topography to better understand mining behavior. However, while administrative digitalization has seen some progress, the application of these technologies at the operational level presents significantly greater challenges.

In small-scale mining, individual managers often oversee entire units, unlike larger operations that rely on specialized teams. The high cost of trial-and-error in technology implementation, combined with a lack of technical expertise among the workforce contributes to resistance to change. Efforts to integrate professionals from medium- or large-scale mining have failed due to their limited understanding of the unique economic and operational realities of small-scale mining, such as processing through third-party plants and the associated pricing risks.

Furthermore, the lack of financing options exacerbates these barriers. Banks in Chile typically do not provide adequate financial backing due to limited knowledge of the small-scale mining sector. The same applies to the other LA countries studied. While institutions such as ENAMI (National Mining Company) provide limited loans for equipment purchases and investment continuity, there are no specific instruments for technology implementation. CORFO (Chilean Economic Development Agency) offers more robust innovation funding mechanisms, but their complexity often prevents small-scale miners from accessing them, particularly due to the lack of dedicated personnel for grant applications. Moreover, there does not appear to be a specific focus on funding operations and technology adoption in mining.

In the case of medium-scale mining in Chile, companies generally recognize the importance of technology, though many are still in the process of adoption. According to (CESCO and Deloitte, 2024) 38% of medium-scale operations indicated that technology is important but still being implemented, while 23% stated that it is fundamental and have already adopted multiple technological solutions. Meanwhile, 15% consider technology to play a limited role, and another 15% have not implemented any technological solutions at all.

Since 2015, large-scale mining operations have underwent significant technological modernization. The introduction of Industry 4.0 technologies was primarily driven by the need to enhance productivity, achieving higher output with fewer workers, reduced processing time, lower energy consumption, and minimized water usage. In addition, security of labor in extracting and processing stages is also a major driver of I.4.0 and AI technologies adoption.

Nevertheless, despite the broad discourse in favor of digitalization and Industry 4.0 in mining and their potential benefits, the autonomous equipment implementation, for example, has remained limited. In Chile, only five large-scale operations, Escondida (BHP), El Teniente (CODELCO), Collahuasi (Collahuasi), Los Bronces (Anglo American), and Los Pelambres (Antofagasta Minerals), have advanced sufficiently to deploy such technologies. These operations have sufficient financial resources, technological infrastructure, and organizational capacity to support large-scale automation. In contrast, the majority of mining sites face significant economic and technical barriers, which restrict their ability to adopt autonomous systems and, consequently, prevent them from engaging fully in such technological transition.

In the case of Colombia, the structure of the mining sector differs substantially from that of Chile, resulting in a distinct pattern of adoption of industry 4.0 technologies. In terms of its production profile, coal is the country's primary mining product, accounting on average for more than 80% of the sector's total contribution between 2020 and 2023, followed by precious metals, which represent approximately 10% of the total in the same years. With respect to its operational structure, 61% of mining titles in 2024 corresponded to small-scale mining, followed by 37% to medium-scale operations and only 2% to large-scale mining (Agencia Nacional de Minería, 2024).

In addition, interviewees emphasized that small-scale mining operations exhibit the highest accident rates in the region and tend not to incorporate Industry 4.0 technologies into their processes. Although the mining sector acknowledges the potential of automation, particularly as means to enhance safety conditions, its implementation remains highly complex in small-scale coal and precious metals mining.

The high informality rate in the sector restricts the adoption of advanced technological solutions in this segment.

In Peru, progress in the incorporation of Industry 4.0 technologies is observable, particularly among large-scale and internationally connected mining companies. Major operators such as BHP, Glencore, Chinalco, MMG Limited (Las Bambas), Hudbay Minerals, and Freeport-McMoRan (Cerro Verde) have begun integrating technologies such as automation systems and advanced environmental monitoring tools into their operations. For instance, Chinalco has recently implemented an integrated operations center at its Toromocho mine. Likewise, the Quellaveco mine, operated by Anglo American, was designed as a fully digital operation from its inception, incorporating an integrated operations center, autonomous haul trucks, and drone-based monitoring systems to supervise on-site operational conditions.

Technological adoption is primarily concentrated among large-scale companies, which perceive digitalization as a strategic necessity, especially in areas related to safety and environmental performance. While there is no specific national regulation mandating digital transformation or efficiency targets, increasing international certification requirements and global environmental standards are generating pressure to modernize operations.

Nevertheless, interviewees emphasized that the implementation of Industry 4.0 technologies in Peru can still be characterized as being at an early stage compared to Chile, with diffusion concentrated among a limited group of leading firms rather than extending across the whole mining sector.

In Brazil, the adoption of 4.0 technologies is being mainly driven by large mining companies such as Vale and Votorantim, that are also introducing integrated operations centers. Interestingly, Vale is often leading the process of 4.0 technologies adoption in collaboration with its suppliers and with universities, responding to requests coming from its customers as well as society at large to improve its security, its water usage and waste treatment. The Brumadiño disaster induced a reconsideration of most activities to reduce risks, and the adoption of advanced digital technologies helped in this regard.

3.1.2 Motivation and drivers of Industry 4.0 technologies adoption

The implementation of Industry 4.0 technologies in the Chilean mining sector has been shaped by a unique combination of external influence, contextual adaptation, and cultural resistance. Unlike countries such as Australia and Canada, where the adoption of advanced digital and remote technologies was primarily driven by environmental challenges, such as extreme temperatures and vast geographical distances, in Chile, implementation initially followed a reactive and imitative model rather than a strategic response to local operational needs.

The Integrated Operations Centers offer a clear example of this attitude. In Australia, these centers emerged out of logistical necessity, enabling remote coordination across isolated operations. In Chile, however, their adoption was significantly delayed, and occurred nearly 15 years later, despite earlier studies recognizing their potential. For a long time, the perceived complexity of such systems, coupled with uncertainty and difficulty to measure their exact long-term value, inhibited local adoption. It was not until the COVID-19 pandemic that these systems were rapidly implemented, as managing operations remotely became an essential condition for business continuity.

Importantly, one of the initial drivers of digitalization in Chile, as well as in other Latin American countries, was not productivity but safety. The need to remove workers from hazardous environments motivated the first steps toward remote operations. This shift in perception, seeing technology as a means of risk mitigation, helped catalyze the implementation of remote-control systems and automation in critical operations. Further momentum came during the early 2000s with the entry of international private mining corporations, many of which brought technological practices already in use in operations in Canada and Australia with them. These companies introduced new expectations of higher efficiency, better systems integration and data-driven decision-making, which gradually influenced local practices.

3.2 The benefits, costs, and expected results of Mining 4.0 adoption

The adoption of Industry 4.0 technologies in the mining sector has been accompanied by a wide range of expected benefits, associated costs and outcomes. While some impacts are already observable, others are expected as implementations continue to evolve. This subsection provides an overview of these dimensions to assess the broader implications of technological upgrading and 4.0 adoption in the sector.

Benefits and costs of adopting Mining 4.0

3.2.1 The case of the Integrated Operations Centers

Today, the majority of large-scale mining companies operating in Chile, such as Anglo American, Antofagasta Minerals, BHP, Codelco (some mine sites), and TECK; as well as companies in Brazil, such as Vale and Votorantim; in Argentina, such as Barric Gold; and in Peru, including Anglo American and MMG have established Integrated Operations Centers (IOCs) as part of their digital transformation strategies.

One of the most significant advantages is the improvement in personnel quality of life. Remote operations eliminate the need for daily travel to mine sites, reducing worker exposure to hazardous conditions such as dust and extreme weather, while also generating cost savings on transportation, protective clothing, and on-site logistics.

From an operational perspective, IOCs enable real-time communication and coordination between previously siloed departments, such as dispatch and processing plants. Traditionally, mining and crushing operations functioned independently, with the mine focusing solely on ore extraction and delivery to the crusher. With the integration enabled by IOCs, greater visibility and control over ore quality and feed parameters have been achieved. Deviations in crushing plant inputs can now be immediately communicated back to the mine, enabling proactive adjustments and improved process optimization.

IOCs also play a crucial role in safety monitoring. A great example is geomechanical monitoring, which is essential for maintaining mine safety and stability by tracking changes in rock masses, underground structures, tunnels, and active excavations. These systems can combine real-time monitoring, 3D visualization of the mine, and high-precision instrumentations, and when integrated into IOCs they

enable immediate alerts and coordinated responses in the event of ground stability issues, further enhancing worker safety.

Nevertheless, one of the main challenges related to the implementation of the IOC is the persistence of a parallel organizational structure alongside the new operations center. This redundancy results in overlapping responsibilities, adding complexity and increasing operational costs instead of delivering the expected synergy. A central issue is the reluctance to fully abandon traditional models of control and management. As a result, digital tools and human-centered practices continue to operate simultaneously, preventing the consolidation of a unified operational model. This also explains why senior management often fails to perceive the real value of the IOC: the overall way of operating has not fundamentally changed. Even if technology performs well, it cannot deliver its full benefits when embedded in an operational structure that remains misaligned with digital processes.

3.2.2 Benefits and costs of mining equipment automation

Drilling equipment is performing well under automated routines, but trucks remain a greater challenge due to operational complexities, safety restrictions, and human oversight. In practice, trucks depend heavily on operating conditions that are not always stable or well-controlled. For example, although speed limits are set for safety and efficiency, these restrictions are not consistently respected in manually operated trucks. Autonomous trucks, on the other hand, can recover time lost due to human breaks, such as meals, or rest periods, but they require near-perfect operating conditions to function effectively. This means that several design and operational parameters must be adjusted before automation can deliver its full potential, hinting that human operators remain indispensable at this stage, also in adjusting and “training” the new automated systems.

3.2.3 Costs and expected results of 4.0 technologies in small-scale mining

The adoption of Industry 4.0 technologies in small-scale mining faces considerable challenges. Despite the expected benefits, such as increased efficiency, improved traceability, and reduced environmental impact, the high capital investment and operational costs pose major barriers. In many cases, small-scale operations lack financial resources and the specialized workforce required to implement and manage advanced technologies. Additionally, limited digital infrastructure and poor connectivity in remote mining areas further restrict access to these solutions. Nevertheless, when such technologies are adopted, they have demonstrated measurable improvements in operational performance and sustainability. As such, advancing the professionalization of small-scale mining and expanding access to appropriately scaled, context-specific technological solutions will be essential for unlocking the full potential of Industry 4.0 in this segment of the industry.

3.2.4 Medium-scale mining

Regarding the Chilean medium-scale mining (CESCO and Deloitte, 2024), the primary expected benefits of new technologies include reducing operational costs (89%), increasing productivity (78%), and improving operational efficiency (78%). However, medium-scale mining operations face significant challenges, particularly regarding limited financial resources, infrastructure, and access to specialized knowledge. The disparity in technological maturity across companies in the sector highlights the need for more structured and targeted support to foster widespread innovation. This disparity arises from

the heterogeneity within this segment, which spams a wide spectrum: some firms operate with financial capacity and production levels not too distant from those of large-scale mining, while others operate under conditions more similar to small-scale mining.

Addressing this heterogeneity requires targeted support mechanisms and the development of focused technologies that respond to the diverse realities of mining operations. In this context, universities play a critical role by bridging knowledge generation with industry needs. A notable example is the Advanced Mining Technology Center (AMTC) at the Universidad de Chile, which has become a leading hub for research and innovation in the sector. Through collaborative projects, the AMTC develops technological solutions tailored to the operational and economic conditions of different mining segments, thereby enabling more inclusive and effective innovation pathways across the industry (Box 3). Similar experiences have been detected in Brazil and Colombia.

Box 3. UNIVERSITIES AS CATALYSTS FOR INNOVATION IN THE MINING SECTOR

The Advanced Mining Technology Center (AMTC) of the Universidad de Chile was founded in March 2009 after being awarded funding through the *Associative Research Program* of CONICYT, under the framework of the *Basal Funding for Scientific and Technological Centers of Excellence*. Its mission is to generate world-class multidisciplinary research, transfer innovative technologies, and train advanced human capital, thereby contributing to responsible mining that ensures both national wellbeing and global development.

The AMTC is organized into five research groups: (i) exploration and ore deposit modeling, (ii) mine planning and design, (iii) mineral processing and extractive metallurgy, (iv) mining automation, and (v) water and environmental sustainability. This structure enables the center to address mining challenges from a holistic perspective, integrating geosciences, engineering, environmental sciences, and automation into comprehensive solutions. Importantly, AMTC maintains strong synergies with the academic departments of the Faculty of Physical and Mathematical Sciences at the Universidad de Chile, fostering multidisciplinary collaboration across fields.

Unlike private suppliers, who often focus primarily on large-scale mining clients due to their higher financial capacity, AMTC is positioned to develop technologies and knowledge tailored also to the medium- and small-scale segments, which remain underserved by commercial providers. This orientation enhances inclusivity in mining innovation by expanding access to cutting-edge solutions beyond the largest operations.

Since its establishment, AMTC has achieved a substantial research and development footprint. Its record includes more than 1,000 indexed publications in national and international journals and conferences, over 560 collaborative projects with mining companies, suppliers, and academic institutions, and more than 200 competitive research projects awarded. In 2024 alone, the center executed approximately USD 8.2 million in R&D investment. Its technology portfolio includes 20 patents, 54 registered software tools, and two technologies at different Technology Readiness Levels (TRLs). Collectively, these outcomes position AMTC as a regional leader in mining research and innovation, bridging academic excellence with industrial application.

Source: AMTC. (2025). 16 years of the Advanced Mining Technology Center, and authors' interview.

Industry 4.0 adoption in Brazil's medium-scale mining sector remains emergent and heterogeneous. While the country has a sophisticated Mining 4.0 ecosystem led by large corporations such as Vale, most medium-scale mining companies are still in the early stages of digital transformation, prioritizing

incremental technologies such as cloud computing, IoT sensors, process integration, and data analytics rather than fully autonomous or highly integrated mining operations (Eichholg, 2021).

3.2.5 Industry 4.0 and sustainability benefits

In recent years, the imperative of sustainability has become a central driver for the adoption of Industry 4.0 technologies in the Latin American mining sector. The growing demand for environmental accountability, both from investors and regulatory frameworks, has led mining companies to increasingly integrate advanced monitoring systems and sensor-based technologies to track environmental variables such as dust emissions, water contamination, and the presence of hazardous waste. These tools are critical not only for compliance but also for proactive risk management, as environmental incidents now have the potential to halt operations and significantly damage corporate reputation.

Companies are beginning to recognize that any operational improvement, whether in energy use, water efficiency, or process optimization, can translate into measurable sustainability gains. As such, the narrative around Industry 4.0 has evolved from being purely cost- or efficiency-driven to being a critical component of sustainable resource management.

Moreover, investors and international markets are increasingly demanding transparency and environmental certification, further incentivizing the adoption of digital tools that can provide traceability, real-time monitoring, and reporting capabilities. The link between operational efficiency and sustainability performance is becoming more explicit, reinforcing the need for mining companies to adopt integrated, data-driven approaches. Interestingly, an unexpected positive externality that was generated by the use of digital solutions and remote control of operations was the reduction in road traffic and the lower use of energy in the mine.

In Chile, a significant regulatory shift occurred with the enactment of the Economic and Environmental Crimes Law in 2023, which imposes criminal liability, rather than just financial penalties, on senior executives for severe environmental violations. Offenses related to water contamination, unauthorized alteration of natural water courses, and airborne particulate emissions are among the most heavily sanctioned. This legal change has elevated environmental compliance to a top corporate priority, triggering a surge in the deployment of environmental monitoring technologies and early warning systems.

While Industry 4.0 technologies are often introduced with the stated objective of enhancing productivity, that is doing more with fewer people, in less time, using less energy, water, and resources, they do not inherently create value on their own. Rather, they function as facilitators, enabling companies to operate more cleverly and sustainably when embedded within a broader framework of strategic planning, workforce training, and environmental responsibility.

3.3 Enabling factors for successful deployment of Industry 4.0 technologies

While the mining industry has been progressively adopting Industry 4.0 technologies, their successful deployment is driven by a number of key enabling factors that have yet to be fully developed.

3.3.1 Economic and organizational impact

While the economic value of the IOC and automation is widely acknowledged across the industry, it is not yet fully quantifiable. This uncertainty remains one of the key reasons why the adoption of Industry 4.0 technologies continues to progress slowly. Many companies still lack a clear understanding of the expected economic benefits, particularly when initial investments do not immediately translate into measurable productivity gains or cost reductions. As a result, current adoption is often driven less by rigorous economic evaluation and more by a combination of other factors: (i) emulation of leading companies that have already implemented these systems, (ii) the relatively low marginal cost of adding certain digital tools compared with other forms of capital investments, (iii) the perception that declining ore grades will eventually require more sophisticated technologies to maintain competitiveness, and, (iv) growing internal and external pressures to improve safety and increase environmental sustainability. However, the realization of these benefits remains constrained, in large part by the persistence of outdated operational structures that have not been redesigned to align with digital practices. The coexistence of traditional and digital routines creates duplications and redundancy in roles and responsibilities, limiting efficiency gains. At the same time, gaps in maintenance capabilities, insufficient digital competencies, and pockets of resistance to organizational change further restrict the effective deployment of these technologies.

3.3.2 Organizational barriers

The success of technology implementation often hinges on an effective organizational culture and change management capabilities. In Chile, companies tend to expect technology to adapt to their existing processes, while in other countries like Colombia, there is more openness to adapting operations to new technologies. This cultural rigidity can hinder adoption and slow progress.

Besides that, the generational shift within the workforce, from older, more traditional supervisors toward younger, more data-centric engineers and analysts, is expected to enable the mining industry to realize the full potential of these innovations. The new generation is more comfortable interpreting data, trusting automated routines, and optimizing operations in real time.

3.3.3 Skills for the Industry 4.0

According to CESCO and Deloitte (2024), medium-scale mining companies in Chile consider the main challenges related to technological adoption to be personnel training in the use of new technologies (78%), followed by system integration and employee resistance (67% each), and lack of financial resources (33%).

In terms of skills and capabilities, this transformation has demanded the recruitment of data analysts and data scientists to enable advanced data processing and operational optimization. At the same time, maintenance crews exhibit a skills gap, as they are not yet trained to service and repair these sophisticated and specialized systems. This points to a growing need for training programs and upskilling initiatives within the industry.

3.4 Value chain transformation

The increasing adoption of Industry 4.0 technologies in the industry, especially by the largest corporations, has not changed the organization and governance of the value chains in fundamental ways. However, some changes could be detected, and some new windows of opportunity are opening.

3.4.1 Suppliers role in digital transformation

Suppliers have undergone a significant transformation in their capabilities. Small companies and service providers from Chile are delivering increasingly sophisticated digital solutions. Previously, suppliers predominantly provided isolated robotic components; today, their portfolios encompass integrated and data-centric solutions tailored to each mine's operational profile.

The technological advancements have opened the market to new suppliers, for instance, companies from India, who bring specialized expertise in software, data analytics, and digital technologies that were previously unavailable in the industry in the region. This expansion of the supplier ecosystem is a key enabler for the ongoing digital transformation in mining.

Box 4. AN EXAMPLE OF A CHILEAN EMERGING AND DYNAMIC SUPPLIER

TIMINING is a dedicated mining software company with over 10 years in the market and headquartered in Santiago. They create software that transforms raw data into insights to help mines run more efficiently, safely, and sustainably. They employ experts in data integration, advanced analytics, remote 3D visualization and user experiences design.

TIMINING has experienced rapid international growth, with clients in at least eight countries, including Chile, Peru, Colombia, Australia, Brazil, South Africa, and Canada. Its digital twin and analytics tools are currently deployed in more than 30 major mining operations worldwide, where they contribute to operational efficiency and risk management. Specifically, these tools help reduce reconciliation times, the systematic process of comparing planned mining metrics with actual production data; improve slope design compliance, by ensuring that excavation practices adhere to geotechnical and safety specifications; and increase operational transparency, through real-time data integration and visualization.

In November 2023, TIMINING closed a Series B investments, which is the second major round of venture capital funding, of about USD $10 million, led by Kayyak Ventures and other institutional investors. This funding aims to consolidate their presence in mature markets such as North America, Australia, and the Asia-Pacific region, expanding the impact of their solutions in large-scale mining.

Sources: *TIMining. Digital Solutions for Smarter, Safer, More Productive Mines.* From: https://www.timining.com accessed on 4.8.2026.
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3.4.2 Market dynamics and contract miners

The presence of contract miners, that are specialized external firms that undertake core operational activities such as drilling, blasting, hauling, maintenance, and production planning, has grown

significantly worldwide, particularly in countries like Australia and Indonesia. In these countries, large contract-mining groups operate multiple mines. In contrast, Chile and Peru have far fewer contract miners, and most operations remain owner-operated, even though in practice many owners already subcontract a wide range of tasks.

The model becomes especially attractive when owners have high-quality assets but prefer to create competitive procurement environments that drive efficiency, reduce capital intensity, and open space for innovation. As highlighted by Peña, Ríos, and Espinoza (2024), contract mining allows owners to focus on strategic decision-making while transferring operational complexity to firms with specialized capabilities and economies of scale. Integrating this model more widely in Chile could reshape the mining value chain by introducing more specialized operators, increasing competition in services, accelerating the adoption of new technologies, and enabling more flexible, modular, and innovation-driven production systems across the sector. However, this has not occurred yet in Chile and Peru, probably limited also by the large size of most operations.

3.4.3 Global innovation hubs and digital natives' companies

The geographic hubs of mining innovation have gradually shifted as the industry has evolved. With the rise of the digital revolution, mining expanded into more remote areas, prompting the emergence of new development centers also in countries such as Russia, South Africa, and Western Australia. Talent mobility has significantly shaped this landscape; for instance, many mining-tech improvements in Australia were led by South African professionals. In this context, proximity to the mine has become increasingly important. Even when strategic or research centers are located elsewhere, much of the practical innovation is now developed near mining operations, where solutions can be tested, iterated, and validated under real conditions (personal communication with one of the interviewees, June, 2025).

Within this evolving ecosystem, digitally native companies play a central role. These are firms that are born directly in the digital environment, are typically cloud-based since their inception and often supported by private funding in their early stages. Unlike traditional companies, they do not need to undergo a process of digital transformation; technology is their starting point and foundational identity. As a result, digital tools, data-driven processes, and automation are not add-ons but integral to how they conceive, design, and deliver solutions. Their inherent technological orientation allows them to integrate more fluidly into the mining innovation landscape, responding quickly to operational needs and contributing to the sector's ongoing digital evolution

When it comes to suppliers, Chile has developed a significant knowledge and innovation hub whose capabilities are now expanding internationally. This is clearly occurring faster in Chile than in Colombia or Peru. Over the past decade, the mining supplier ecosystem has undergone a marked process of professionalization, evolving from a market driven primarily by price competition into one characterized by high-quality specialized solutions. In areas such as industrial software, digital systems, and advanced supply-chain services, Chilean firms have built expertise that is both sophisticated and globally competitive.

5. Conclusions and Public Policy Implications

The transition toward Mining 4.0 and AI is progressing in Chile and Latin America, but its speed and depth vary significantly across firms, largely determined by financial capacity and scale. While large mining companies have begun integrating advanced digital tools, automation, and robotics, smaller firms continue to face substantial barriers to adoption. This asymmetry underscores the need for targeted public support, including digitalization programs, financing instruments, and technology-extension services—to ensure that the benefits of Industry 4.0 diffuse beyond major operators.

A second challenge lies in the need for context-specific technological solutions. Mining conditions in Latin America—characterized by declining ore grades, increasing geological complexity, and remote locations—demand tailored innovations rather than generic industrial technologies. As grades continue to fall, maintaining viable operations will become unattainable without adopting advanced digital capabilities.

Human capital will be a decisive enabler. The adoption of complex digital systems requires upgrading skills, especially in areas such as high-precision maintenance, sensor integration, data analytics, and AI-driven operational optimization. Strengthening R&D incentives, tax credits, and collaborative research programs will also be essential to foster innovation that responds to local mining challenges. In this regard, the recently published draft of the Critical Minerals National Strategy in Chile provides an opportunity to plan new initiatives linked to Mining 4.0 (Ministerio de Minería de Chile, 2026).

Looking forward, Artificial Intelligence is expected to transform mining operations, enabling more autonomous decision-making, real-time optimization, and improved safety outcomes. Yet many mining firms, including large operators, adopt new technologies slowly—not due to lack of interest, but because they lack clear pathways, internal capabilities, or mechanisms to evaluate and integrate emerging solutions.

There is a significant opportunity for public policy to support innovation in mining, but Chile has not fully prioritized this sector despite its strategic importance. Targeted support for mining-focused technologies, especially in funding and testing environments, could unlock potential.

In this context, strengthening public–private cooperation becomes central. Effective technological modernization requires institutional architectures that support coordination between government agencies, mining firms, suppliers, universities, and digitally native start-ups. Public policies should therefore promote shared testing environments, joint standards, open innovation platforms, and cross-institutional governance mechanisms.

The adoption of Industry 4.0 technologies offers a transformative opportunity to reconceptualize environmental management in mining by moving from isolated monitoring practices toward a comprehensive ecosystem-based approach. Large-scale mining has already advanced toward automation, integrated operational systems, and increasingly sophisticated data use, not only to understand what is happening in real time, but to anticipate the future. Sustainability pressures are accelerating this trend, driving the installation of more sensors capable of measuring water quality, soil conditions, groundwater contamination, dust emissions, and the contribution of legacy environmental liabilities. These technologies enable the simultaneous observation of multiple environmental dimensions and the generation of integrated datasets that capture cumulative impacts. For the State,

this creates the chance to require holistic, continuous environmental information and to monitor mining operations as interconnected ecological systems.

Additional areas of improvement, where policy support would have high impact, include strengthening cybersecurity and advancing the digitalization of the processes granting and obtaining permissions. These often represent remarkable bottlenecks in project development, with lengthy, fragmented and paper-based procedures that delay investments and complicated coordination across agencies. Reforms should facilitate faster approvals, reduce bureaucratic delays, and align the mining value chain with broader digital transformation goals at the national level.

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