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Innovation in the mining industry: a review of recent technological developments and current trends

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Declaration of Authorship

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet."

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Abstract

Innovation plays a critical role in the mining industry as a tool to improve the efficiency of its processes, reduce costs, but also to meet the increasing social and environmental concerns among communities and authorities. Technological progress has also been crucial to allow the exploitation of new deposits in more complex scenarios: lower ore grades, extreme weather conditions, deeper deposits, harder rock mass and high-stress environments.

This thesis discusses the importance of innovation for the mining industry and describes the mechanisms by which it is carried out. Includes a review of some of the latest technological developments and current trends. The digital transformation process the industry is going through is analysed, along with other relevant trends that are likely to shape the mining of the future. Additionally, a case study is presented to illustrate the technical and economic implications of developing a step change innovation project.

Keywords: Mining innovation; industry 4.0; digital transformation.

Zusammenfassung

Innovation spielt eine wichtige Rolle in der Bergbauindustrie. Innovation führt zu einer Effizienzverbesserung von Prozessen, zu einer Kostenreduzierung und ermöglicht es, den wachsenden sozialen und ökonomischen Bedenken von Gemeinden und Behörden Rechnung zu tragen. Technischer Fortschritt spielte bereits in den letzten Jahren eine wichtige Rolle bei der Erschließung von neuen Lagerstätten, etwa aufgrund des geringen Erzgehaltes, der extremen klimatischen Bedingungen, in tiefen oder harten Gesteinsschichten oder auch in empfindlichen Ökosystemen.

Diese Masterarbeit beschäftigt sich mit der Wichtigkeit von Innovation und deren Anwendungsmethoden in der Bergbauindustrie. Außerdem enthält sie eine Übersicht über die neuesten technologischen Entwicklungen und die aktuellen Trends. Weiters wird auf die Digitalisierung in der Bergbauindustrie eingegangen und es werden relevante Trends vorgestellt, die mit hoher Wahrscheinlichkeit die Zukunft dieser Industrie maßgeblich mitgestalten werden. Abschließend werden die technischen und ökonomischen Auswirkungen eines Innovationsprojektes in einer Fallstudie erläutert.

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1 Introduction

Over the past decades, the mining industry has had to face a challenging scenario for its operation. Improving productivity to overcome natural factors such as decreasing ore grades, deeper deposits and harder rock mass, combined with an increasing environmental and social awareness have boost the industry to constantly work to enhance their processes along the whole value chain. In this, innovation plays a crucial role by providing suitable solutions to surpass these difficulties, ensuring the continuity and sustainability of the mining activity.

There has been a historical argument regarding the innovative nature of the mining industry. For many, the perception is the one of a conservative and traditional industry, while for others mining represents a trend setting sector, that adopts the latest technologies in its processes (Bartos, 2007). This thesis intends to shed light over this discussion, by analysing the dynamics of innovation in the mining industry, historical and latest technological developments and current trends that will shape the mines of the future.

Nowadays, many relevant actors of the industry claim that mining is going through the first stages of a deep changeover from the hand of digital transformation. It is said that this process could change how mining is done, passing from human-run operations to autonomous or semi-autonomous remote-controlled mines. Independent if fully automated operations are achieved in the near future or not, the digital transformation is already impacting the industry and will continue doing so.

The thesis is organised as follows. First, a general view is provided, analysing the importance of innovation for the mining industry, along with the main drivers and actors involved, and a revision of the historical and latest technological developments. In the following section, the current technological trends are reviewed. A view of the mining of the future is offered, by exploring the impacts of digital transformation in mining and other relevant trends. Finally, a case study is presented to illustrate the technical and economic implications of a step change innovation project.

1.1 Objective

Within the context described above, this thesis aims to characterise the innovation environment in the mining industry, specifically:

- Importance of innovation for the mining industry: relation between labour productivity and innovation.
- Dynamics of innovation in the industry: drivers and actors.
- Historical and latest technological developments.
- Current trends and future of the mining industry.

This document will contribute to improve the understanding on the dynamics and mechanisms involved in the innovation processes, along with analysing the current status and expected future of the mining industry, in terms of technological advance.

1.2 Methodology and scope

This thesis was built through an extensive literature research on the topic, including conference papers and presentations by industry leaders.

The scope of this thesis project covers the mining industry in general and its entire value chain (exploration, extraction, processing and smelting & refining). However, by the nature of the topic, artisanal and small-scale mining have been mostly excluded from the analysis, considering the historical low degree of technological specialisation in this sector. Also, for the illustration and exemplification of certain points made in this document, a special focus has been put in the large-scale copper mining sector and the main copper producer countries.

2 Innovation in the mining industry

Cambridge Dictionary defines innovation as a new idea, method, design or product, as well as its development or use. In general, innovation can be understood as a process of change, through which a new idea or solution is applied in a good, service or productive procedure to create value, meet new costumers' requirements, higher safety or environmental standards, among other goals.

There has been a historical debate whether mining is indeed an innovative industry or not. It is often perceived as a conservative sector, where innovation takes only a secondary position in the concerns of companies. But at the same time, many argue that mining is more likely to be comparable with high-tech industries, considering that it utilises vanguard technologies in its processes, such as automated or remote-controlled machinery, and advanced monitoring systems for the collection and analysis of large amounts of data (Bartos, 2007).

In this chapter, the importance of innovation for the mining industry is discussed. In the first section, the relation between innovation and labour productivity is examined. Then, a general view regarding the innovation dynamics within the industry is provided, exploring the main drivers and actors involved. Finally, a review of the historical and latest technological breakthroughs that have represented step changes in specific processes along the mining value chain is presented, along with the description and analysis of relevant technologies developed in the past decades.

2.1 Innovation and labour productivity

A first approach to understand the relevance of innovation within the industry can be made through the analysis of labour productivity. Technological advances usually have an impact on the output, allowing larger production rates while maintaining a similar workforce, or directly reducing the needed personnel by the automation of processes. Nevertheless, changes in labour productivity of a mine may be caused by a series of other reasons. Natural factors, such as decreasing ore grade and deepening of deposits mean that a larger amount of material in more complex situations must be removed to obtain the same final metallic output, thus impacting negatively on labour productivity. While, in an aggregated view (e.g. when analysing the mining industry of an specific country) the discovery and exploitation of new and better deposits can also impact positively the overall labour productivity (Jara, Pérez, & Villalobos, 2010). On the other hand, in a high-price mineral commodities scenario, companies are willing to compromise their costs in order to increase production (because it is profitable), and therefore, reduce their labour productivity (Fernandez, 2018).

Several authors have analysed the behaviour of labour productivity in specific mining industries in an intend to isolate the effect of innovation. Tilton and Landsberg (1999) first introduced the importance of innovation and new technologies in the growth of labour productivity, while studying the decline and recovery of the U.S. copper industry during the 1970's, 1980's and 1990's. The authors attributed most of the labour productivity increasement in this period to the incorporation of the solver extraction and electrowinning technology (SX-EW), along with the use of larger trucks, shovels and drills, in-pit mobile crushers and conveyor belt systems, computerised scheduling of trucks and real-time process controls.

In a later study, Aydin and Tilton (2000) provided more concrete evidence regarding the previously mentioned. Since the exploitation of new deposits can have an impact on the aggregated labour productivity, the authors built two scenarios to analyse this index between 1975 and 1995: one, considering only the mines operating at the beginning of the studied period, and therefore, excluding the effect of new mines; and the actual situation, including both old and new operations. In Figure 1, the adjusted curve represents what labour productivity would have been if no new mines would have entered in operation in this period of time. As shown, adjusted and actual labour productivity resulted to be not so far different, thus approximately 75% of the productivity growth in the U.S. copper industry over those years came from productivity improvements at individual mines (i.e. innovation and technological advances), despite the exploitation of new deposits.

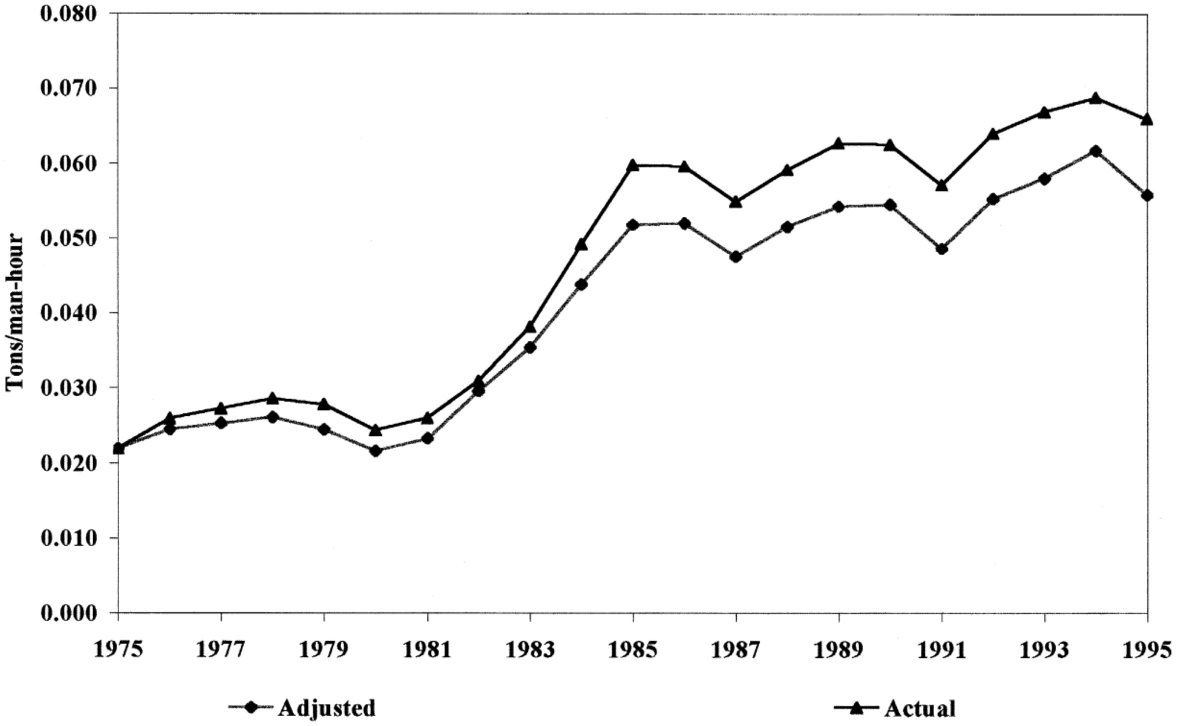

Figure 1: Labour productivity in the U.S. copper mining industry, actual and adjusted to exclude the effects of changing location of output, 1975-1995.
Taken from Aydin and Tilton (2000).

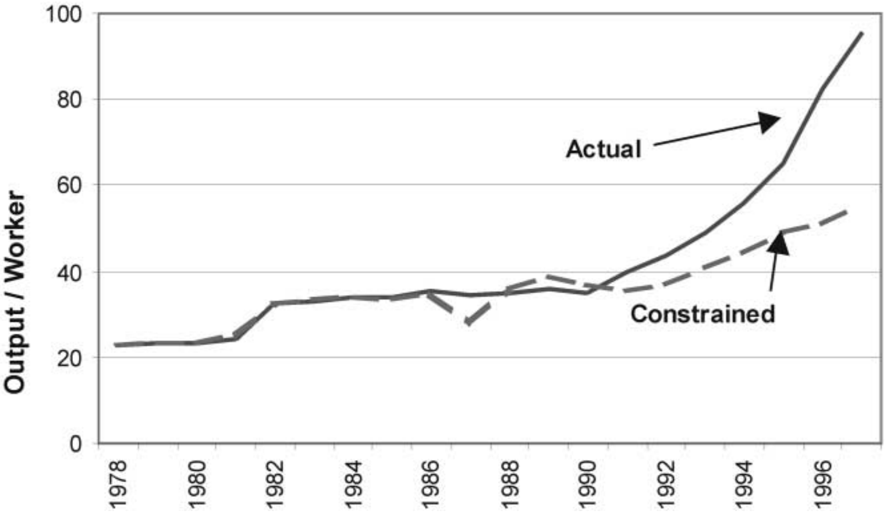

Figure 2: Labour productivity for the Chilean copper industry, actual and constrained (or adjusted) assuming no change in the location of mine output 1978-1997 (tons of copper contained in mine output per copper company employee).
Taken from Garcia, Knights, and Tilton (2001).

Under a similar methodology, Garcia et al. (2001) analysed the labour productivity growth in the Chilean copper industry during the 1978-1997 period (Figure 2). Their findings, though not as dramatic as in the U.S. copper industry, showed that innovation and the introduction of new technologies were responsible for approximately a third of the productivity growth in the total period. Specifically, during the years prior to 1990, this factor accounted for the total growth, while in the 1990's the development of new world-class mines (e.g. Escondida) turned over the scenario. Nevertheless, these results were coherent with the findings of previous studies on the U.S. copper industry, regarding the role of innovation in improving the competitiveness of the mining industry.

More recent research on the copper industry of Chile and Peru have presented additional supporting evidence that, though not the only factor, innovation, including the adoption of new technologies and managerial changes, remains as a key element for the improvement of labour productivity (Jara et al., 2010).

When looking at the following time-period (late 1990's to early 2010's), the situation presents a dramatic change. From 2005 onward, average labour productivity of Chilean mines suffered a sharp decline, as shown in Figure 3. Same situation can be observed in other main mining countries, like Australia, Canada and the U.S. (Figure 4). Labour productivity in these countries started falling on the first years of the 2000's. This decline can be attributed to a combination of natural and economic factors. On one side, while reserves are depleted, ore grades tend to decrease and the operation advances to deeper locations, increasing hauling distances, stripping ratio and geotechnical difficulties, all of which has a negative impact on labour productivity. On the other, in a period of high mineral commodities prices, like the one that the industry went through during the second half of the 2000's and beginning of the following decade, mining companies will favour production growth despite productivity (Fernandez, 2018).

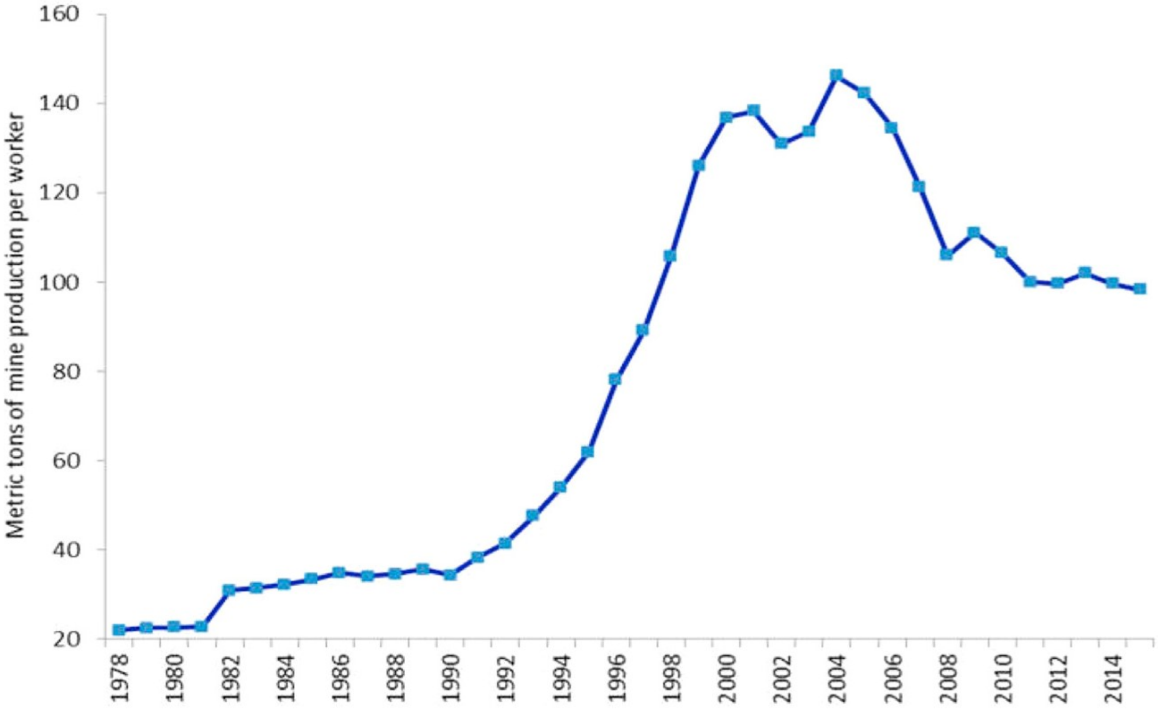

Figure 3: Average labour productivity of Chilean mines for the period 1978–2015. Taken from Fernandez (2018).

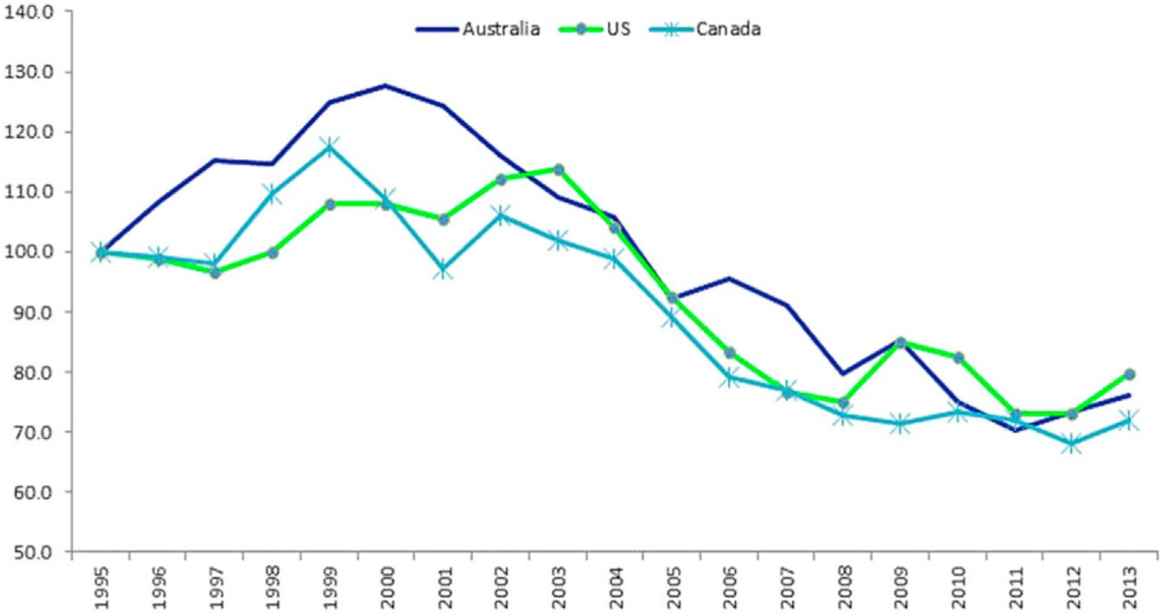

Figure 4: Labour productivity of the mining sector of selected countries, for the period 1995–2013. Annual value presented as a percentage of labour productivity in 1995 (100%) Taken from Fernandez (2018).

As presented, labour productivity is affected by a series of factors, mainly by natural characteristics of mineral deposits, market conditions and innovation. While in periods of labour productivity growth it has been possible to isolate the positive effect of innovation, during declining cycles this task turns more complicated. However, the fall in these periods is attributed mainly to natural and economic factors. In the meantime, innovation remains crucial to maintain the competitiveness of the industry, to the extent possible, providing the methods and tools to overcome the natural challenges faced by modern mines and exploit new and more complex deposits. In other words, while declining of labour productivity may be inevitable during certain periods of time, the development and adoption of new technologies, along with innovation at a managerial level, are essential to maintain mining's competitiveness through the different cycles.

2.2 Drivers for innovation and actors

As discussed in the previous section, innovation constitutes an important factor affecting productivity of mining operations. Examples of technologies developed to improve the efficiency of processes, reduce costs and in consequence enhance productivity, are easily found. Hydrometallurgical production method SX-EW, has been identify as a major responsible for productivity growth in the U.S. copper industry over the last decades of the twentieth century (Aydin & Tilton, 2000). Likewise, continuous mining equipment in underground coal mining, along with draglines and bucket wheel excavators in surface coal mining, were key advances to reach new levels of productivity in coal production. In smelting processes, the development of flash, and more recently, bottom blowing furnaces, has had a great impact in reducing energy consumption and OPEX (more information in section 2.3.2).

Besides boosting productivity, through innovation it has been possible to unlock the potential of deposits that were technically unfeasible to exploit by traditional methods. For example, preconditioning of the rock mass through hydraulic fracturing, confined blasting or a mix of both, has allowed the exploitation of deeper ore bodies, in high-stress environments (for more details, see section 2.3.1).

Addressing safety and environmental concerns has been also a major driver for innovation. Over recent decades, focus has been put in removing workers from critical activities through the automation of processes and the use of autonomous and semi-autonomous (remote-controlled) equipment.

Meeting more rigorous environmental regulations and attending the concerns of local communities are minimal requirements for maintaining the social licence to operate. Therefore, innovation has been also aimed to the development of cleaner and more environmentally friendly solutions in the whole value chain of the business, and not only to improve the efficiency and reliability of its processes (Upstill & Hall, 2006). An example of this are the new tailings disposal methods that have been implemented to reduce the impact of mining on the environment, such as the thickened and paste tailings disposal. These methods improve water efficiency in their processes, reduce the requirement of surface for their disposition, minimise risks of collapse, among other advantages over traditional methods (see section 2.3.3).

Regardless, extractive firms have historically shown low levels of expenditure in research and development (R&D), often perceived as the main innovation-related index (Upstill & Hall, 2006). During the decades of 1990's and 2000's, R&D intensity of relevant mining and mineral companies, understood as the R&D expenditure as a percentage of total revenues, was in average only approximately 0.5% (Filippou & King, 2011).

Figure 5 shows the average R&D intensity for some of the largest mining companies, as revenue level refers, during the 2011-2018 period. Though presenting variation during the period, in average this index has remained around 0.4%. These levels of R&D intensity are considerably low compared to other industries. For example, in 2015 pharmaceuticals and information and communications technology (ICT) equipment, the most R&D-intensive industries, reached levels of 25.1% and 24.7%, respectively. Moreover, the average R&D intensity in 2015, across all industries in OECD countries was 5%, more than ten times the level of the selected mining companies (OECD, 2017).

Measuring the level of innovativeness of an industry by only examining R&D intensity, however, can lead to misinterpretation. Some authors argue that R&D expenditure fails to consider other activities that could be related to innovation efforts, such as engineering development, plant experimentation and exploration of new markets. Also, R&D expenditure in general does not include mineral exploration expenses (Upstill & Hall, 2006). While these arguments may be reasonable, it is necessary to analyse more in detail how and by whom innovation is done in mining.

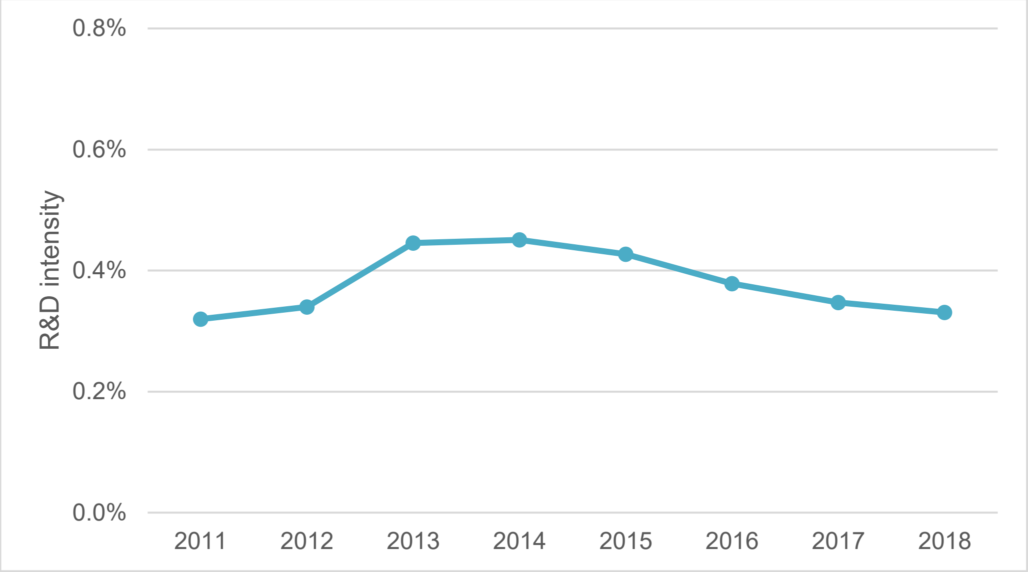

Figure 5: Average R&D intensity of five of the largest mining companies[1], based on 2018 revenues. R&D intensity calculated as a percentage of total annual revenues[2] for the 2011–2018 period.
Sources: Data retrieved from annual reporting of companies Anglo American[3], China Shenhua Energy Company[4], Codelco[5], Rio Tinto[6], Zijin Mining[7].

Whereas in the past mining companies would have tended to develop technology solutions in-house, over the last decades of the twentieth century the tendency changed. Economies of scale from using larger loading and hauling equipment had an important impact in improving productivity and reducing costs. Yet, these solutions came from equipment manufacturers, not from mining companies (Bartos, 2007). This is how outsourcing became a tendency among large producer

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[1] Companies selected according to availability of information (i.e. R&D expenditure informed in annual reports, individualised and separated from exploration expenses).

[2] In the case of Zijin Mining, R&D intensity was calculated as a percentage of total operating income, according to data reported by the company.

[3] Available in: https://www.angloamerican.com/investors/annual-reporting

[4] Available in: http://www.csec.com/shenhuaChinaEn/1382683238772/dqbg.shtml

[5] Available in: https://www.codelco.com/prontus_codelco/site/edic/base/port/memorias.html

[6] Available in: https://www.riotinto.com/investors/results-and-reports-2146.aspx

[7] Available in: http://www.zijinmining.com/investors/Annual-Reports.jsp

firms, resulting in higher degrees of vertical disintegration (Pietrobelli, Marin, & Olivari, 2018). Companies would focus in their core business, while relying in suppliers for the development of technological solutions, avoiding in this way the risks associated to the large investments involved.

Though large global suppliers are important actors for the development of new technologies, the outsourcing tendency previously mentioned has also opened the opportunity for the emergence of local knowledge intensive mining suppliers. These firms hold specific local knowledge that allows them to provide customised solutions for mining companies in niches that are not be covered by the standardised products offered by large global suppliers (Stubrin, 2017).

Also, this outsourcing trend has promoted the creation of collaboration initiatives between large mining companies, local suppliers, governmental and academic institutions for the development of technological solutions. Instances like these can be found in Australia, Chile and Brazil (Pietrobelli et al., 2018). In Chile, for example, the World-Class Supplier Programme, a public-private partnership between the mining companies BHP, Codelco and Antofagasta Minerals; Fundación Chile and other governmental institutions; and more than 75 local suppliers; has already developed over a hundred of innovation initiatives since it was launched in 2009. Though the programme has had a positive impact in the development of the knowledge intensive mining supplier sector in Chile, certain challenges need to be faced to bring this sector to the next level of progress. Among these challenges, it is necessary to escalate the programme, promoting high-impact and long-term innovation projects, despites the usual incremental technological solutions developed until now (Alta Ley, n.d.).

Unlike most mining companies, the supplier sector holds in high priority the innovation agenda. A survey conducted on 432 firms from the Mining Equipment, Technology and Services (METS) sector in Australia, in 2015, revealed that for 63% of these companies innovation was core to their business strategy, driven mainly by a customer-focused vision, the necessity of staying ahead of the competition and direct solutions requirements from their customers (AUSTMINE, 2015).

A similar view shares the knowledge intensive mining supplier sector in Chile. 25 of these companies were surveyed in 2018, revealing that for the 60% of them innovation was core to their business strategy, driven mainly by direct solutions requirements from their customers. The survey also revealed a high level of innovation-aimed expenditure among these firms. 56% of them reported innovation expenses higher than 10% of 2017 revenues, reaching a 23.8% in average (COCHILCO, 2018).

Besides the dynamics involved in the development of technologies, either by mining companies themselves or their suppliers, the mining industry is also recognised for its capacity to adopt technologies from other industries. ICT have facilitated the introduction of important improvements in exploration techniques, mining and processing. Simulations, sensor systems, automation and remoted-controlled operations are some examples (Upstill & Hall, 2006).

Nowadays, ICT offer a new level of technological advance from the hand of digital transformation. The extractive industry finds itself in the early stages of adopting these new technologies. The full potential of their applicability for mining processes is yet to be unlocked. The implications of the current trends of Industry 4.0 for the mining industry are discussed and analysed in chapter 3.

2.3 Historical and latest technological developments

Complementary to the previous sections, in this sub-chapter the evolution of step change technologies developed in the mining industry is examined.

As an industry that relies greatly in economies of scale, innovation in mining is often aimed to the development of solutions that represent an incremental improvement for existing processes. These developments can have a great impact in companies' operations, while representing minor risks compared to non-incremental upgrades. Non-incremental or revolutionary innovations need major changes in the organisation of the operation, new design for plants or equipment, all which involves high costs, thus high risks (Upstill & Hall, 2006).

Accordingly, extractive industry has not seen many revolutionary developments in the last almost 120 years. In his study, Bartos (2007) identified twenty step change technologies since the year 1900, among the different mineral sectors and stages of the mining value chain. To these, three recent developments have been added (marked as * in Table 1), that in the opinion of the author of this thesis, have represented recent technological breakthroughs in the mining industry.

Considering each segment by separate, there have been between one and four revolutionary developments in 120 years. In this matter, and accordingly with the figures reviewed in previous sections, the mining industry distances itself from high-tech industries, and it is positioned closer to mature industries, such as cement and glass industries, which show similar revolutionary development rates over the last century. Conducting comparisons taking the mining value chain as a whole (i.e. exploration, extraction, processing and smelting & refining) for any of the minerals mentioned, could be perceived as questionable. This, because the rest of the industries do not consider upstream processes (e.g. glass and cement start at the processing stage) (Bartos, 2007).

Table 1: Revolutionary mining technologies developed since 1900. Modified after Bartos (2007).

Commodity/procedure	Innovation
Coal	Longwall extraction
	Continuous mining
	Draglines
Copper	Flotation
	SX-EW
Gold	Heap leaching
	Autoclaving
Nickel	Pressure acid leach
Uranium	In-situ leaching
Grade control	Kriging
	Computer modelling
Scheduling	Operations research
	GPS truck location
Surface mining	Large-scale open pit mining
Underground mining	Ammonium nitrate explosives
	Carbide and electric mine lamps
	Rock bolts
	Preconditioning of rock mass *
Comminution	Semi-autogenous grinding (SAG mill)
Smelting	Flash furnace
	Top submerged lance smelting
	Bottom blowing smelting (BBS/SKS) *
Tailings	Paste tailings disposal *

As shown in Table 1, in recent years technologies have been developed in different levels of the mining value chain, impacting productivity, safety, and environmental aspects of operations. The three innovations identified as relevant, in this author’s view, are described in more detail reviewing techno-economical aspects, main features, operations where they have been implemented, along with current and future trends.

2.3.1 Preconditioning

Over the past decades, from 1990’s onward, preconditioning techniques have been applied in underground mining operations. The application of preconditioning has allowed to operate in deep and high-stress environments, by improving caving, fragmentation and stability of underground infrastructure.

There are two types of preconditioning techniques: hydraulic fracturing (HF) and confined blasting (CB). HF was adapted from the oil & gas industry, after research work carried out by CSIRO Petroleum and first applied in Northparkes Mines, New South Wales, Australia, in 1997. HF has also been applied in coal mining for improving coal seam permeability, hard roof control and enhancing top coal caveability (He, Suorineni, & Oh, 2016). On the other hand, CB was first introduced as a mean to reduce rock mass stresses and mitigate rock burst risk in East Rand Proprietary Mines, a gold underground operation in Johannesburg, South Africa, in the early 1950’s. However, it wasn’t until the end of 1980’s and beginning of 1990’s when this technique started to be widely accepted and used to improve safety in high-stress environments and later as a caving-inducing method (Ferreira, 2019).

In present days, preconditioning is widely applied in caving operations in Australia and Chile (Ferreira, 2019; Gottreux, 2016).

General description

Though HF and CB are usually applied in combination, each technique follows different principles.

- Hydraulic fracturing (HF): HF consists in the creation and extension of fractures in the orebody by the high-pressure injection of fluids. For this, boreholes must be drilled in the area of interest and in each one, two packers must be placed. Through them, the fluid is injected and the fracturing, initiated from the borehole, achieved. These fractures create additional joint sets in the orebody, facilitating further cave propagation and fragmentation (He et al., 2016). General schematics of the HF process are shown in Figure 6.
- Confined blasting (CB): By detonating confined explosive charges, CB is aimed to generate new fractures overcoming the resistance of the existing joint sets and reducing the stiffness of the rock mass, thus reducing its ability to accumulate energy (Ferreira, 2019). General schematics of the CB process are presented in Figure 7.
- Mixed preconditioning: HF and CB are usually applied in combination, executing HF first and then CB. This order of execution is based in the hypothesis that the fractures created by HF serve as reflecting surfaces for the waves generated by CB, therefore these waves are concentrated in the zone of interest (Gottreux, 2016).

Main features

Preconditioning allows to modify the structure of the orebody before being mined. The objective is to degrade its geotechnical quality, improving its caveability, fragmentation and stability, and reducing the stress concentration (Ferreira, 2019). With these improvements, a faster ramp-up can be achieved and hang-up risks are mitigated, facilitating a more efficient and safe operation.

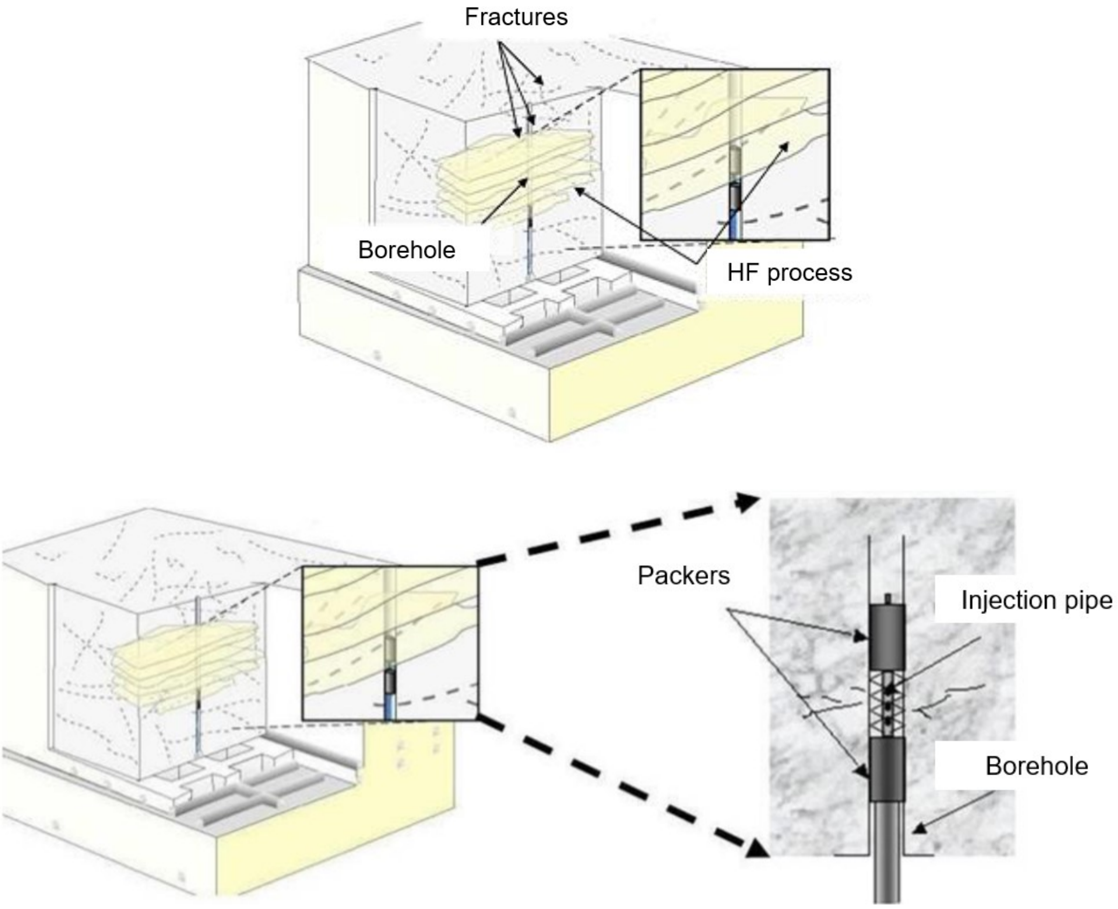

Figure 6: General schematics of HF in cave mining. Boreholes drilled from lower levels. Taken from Gottreux (2016).

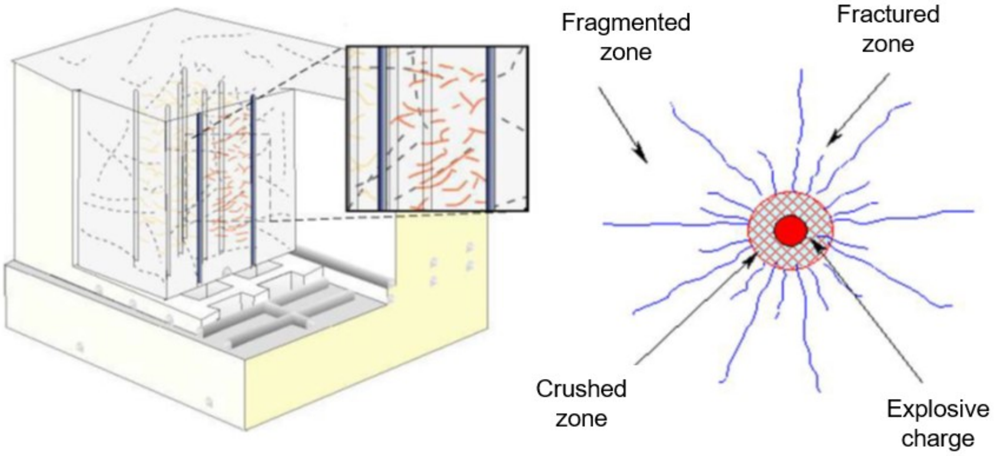

Figure 7: General schematics of CB in cave mining. Generation and opening of fractures and propagation of microfractures (left). Effect of blasting in the confining rock (right). Taken from Gottreux (2016).

Operations and projects

Preconditioning in its three versions (HF, CB and mixed) has been applied in several caving operations in Australia and Chile (Ferreira, 2019; Gottreux, 2016):

- Australia: Northparkes (CMOC and Sumitomo Group) and Cadia East Mine (Newcrest Mining).
- Chile: Andina (Codelco), El Teniente (Codelco) and Salvador (Codelco).

New block caving projects, such as Chuquicamata Underground Mine (Codelco) in Chile, also considers the application of mixed preconditioning. Its operation is planned to start on 2019.

Current and future trends

Preconditioning constitutes a proved and validated technique, widely applied in massive caving operations in Australia and Chile. Nevertheless, further studies could be conducted to improve the understanding of the effect of preconditioning on secondary fragmentation, impact of geological environment on preconditioning performance, among other topics.

Preconditioning is also likely to be affected by the process of digital transformation. Automated charging of explosives and wireless detonators are examples of how the preconditioning activities could be carried out in the near future, improving safety by removing the workers from these critical activities, and enhancing productivity by reducing operational interferences. These innovations should also open the opportunity to make viable the operation in complex areas, such as subsidence and landslide sectors, overcome extreme weather conditions and operate with vertical slopes and multiple benching (Peña, 2018).

2.3.2 Bottom blowing smelting (BBS/SKS)

Smelting and refining, all together, represent the last stage in the production process for several metals. Such is the case of copper extracted from copper sulphide minerals. By the application of heat in the smelting phase, and electrical current in refining, the concentration of copper in the product is progressively increased, as shown in Figure 8.

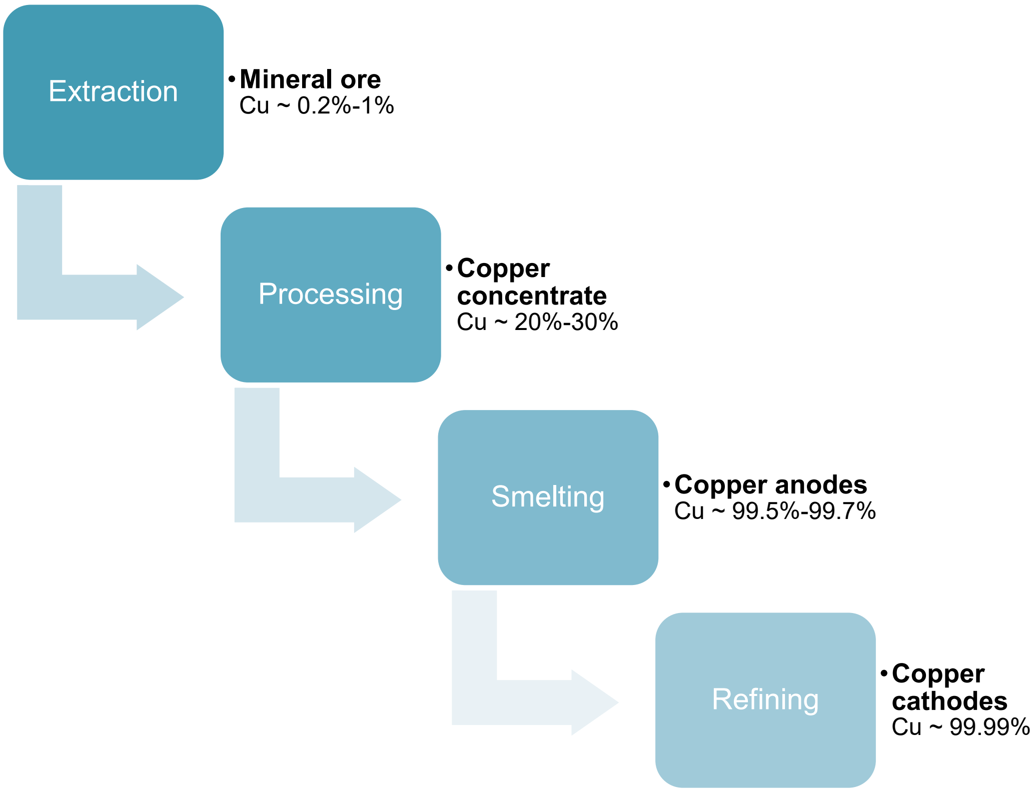

Figure 8: Simplified flow process of copper production.

The complete smelting process is usually carried out, consecutively, in three furnaces: smelting, conversion and anode furnace, respectively, being the first one the core stage.

The existing smelting technologies can be classified in three main groups: flash smelting, bath smelting or mixed. By 2015, flash technologies held 43% of world's copper smelting capacity across 22 operations; bath was responsible for 34% of the smelting capacity, correspondingly to 23 operations; the remnant 10% corresponded mainly to mixed systems (10 operations). However, from the year 2000 onward there has been an increasing tendency for preferring bath technologies despite flash furnaces (COCHILCO, 2015). This trend has been especially strong in China, who has become the main copper smelter & refining actor, accounting for more than 37% of world's concentrate processing capacity by 2017 (Cifuentes, 2018). Moreover, 40% of this capacity was supported by the BBS/SKS technology (Xu, 2018).

Bottom blowing smelter, BBS, or SKS as short for ShuiKouShan, place of origin of the technology, is one of the recently developed bath smelting furnaces. Though the first pilot test took place in 1999 at the ShuiKouShan lead smelter in Hunan, China, it wasn't until 2008 when the first commercial application was implemented in Sin Quyen Copper Smelter, Vietnam. Then, in the same year, the second commercial application, and first one in China, came into operation in Dongying Fangyuan Phase I copper smelter, which has been crucial for the development and improvement of the technology. Since then, more than 10 smelters have been built with the BBS/SKS technology (all of them in China), attracting the attention of the industry due to its remarkable productive and environmental performance (Coursol, Mackey, Kapusta, & Valencia, 2015; ShuaiBiao, 2016).

General description

The BBS/SKS furnace is a cylindrical vessel which actual dimensions vary from one smelter to other. The wet copper concentrate is fed to the reactor through the feeding mouths at the top. In the same location, but at the bottom of the furnace, are located the oxygen injectors. On the sides are the off-gas duct (at the top), matte and slag outlets. Additionally, auxiliary burners are in each extreme of the vessel to be used during the initiation or stand-by stages. This configuration allows the existence of an agitated oxidation zone (above the injectors) and a settling zone (over the outlets), where the matte rich in copper (70%-75%) separates from the slag due to density differences (Coursol et al., 2015). The arrangement can also vary, having the feeding holes and oxygen injectors in the middle (as shown in Figure 9), or putting these on one side of the vessel and the off-gas, matte and slag outlets on the other.

The main differences between BBS/SKS reactors and other bath smelting technologies are the location of the oxygen injectors and its high level of oxygen enrichment (up to 75%). These bring a series of benefits, detailed as follows.

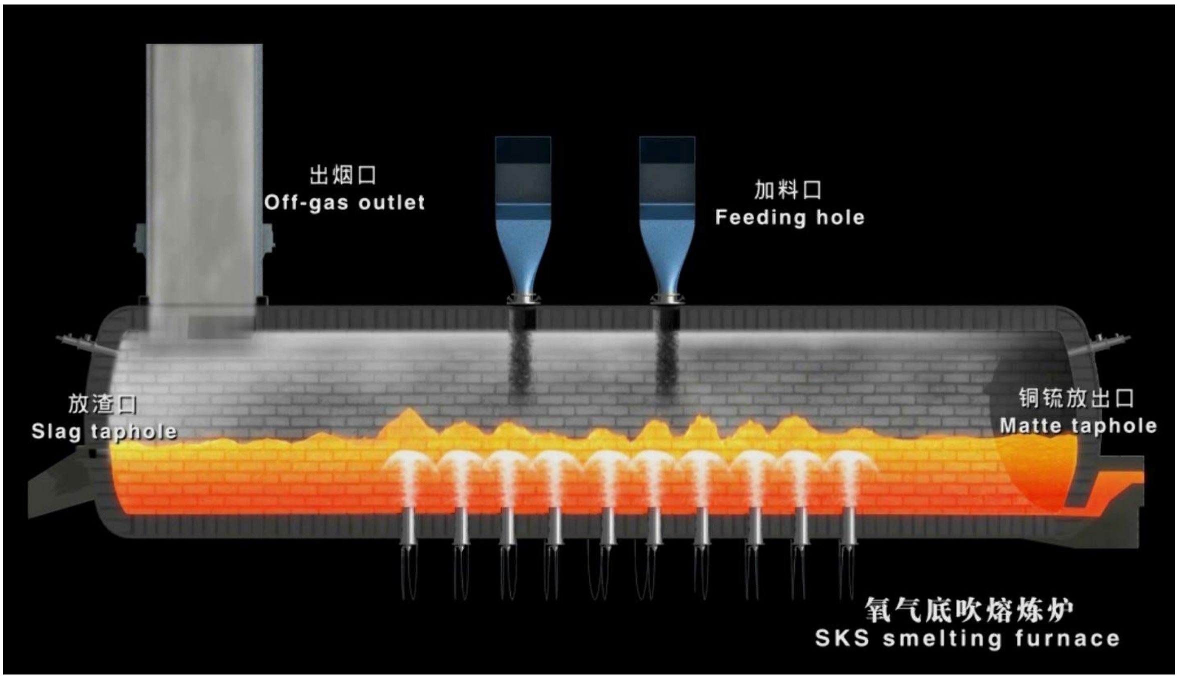

Figure 9: General schematics of a BBS/SKS furnace.
Taken from Xu (2016).

Main features

BBS/SKS technology have shown several advantages over other smelting technologies. According to recent studies (Coursol et al., 2015; Jie, 2016; LiBing, 2016; ShuaiBiao, 2016; Xu, 2018), these can be summarised as follows:

1. Heat efficiency and low energy consumption:
    a. The vessel is bricked with refractory, which reduces heat losses by radiation. Only the outlets are covered with water jackets.
    b. The highly oxygen enriched air is injected directly to the matte layer, increasing the efficiency of the process, releasing more heat and in consequence, under the appropriate content of Fe+S (around 40%), allowing an autogenous reaction. With this, the consumption of energy and fuel is lower than in other smelting processes.
    c. High oxygen enrichment also reduces the off-gas volume produced, having lower heat losses by this mean.
2. Flexible and safe operation:
    a. Additional heat from fuel can be used to produce more copper by incorporating low-grade concentrates. The high level of heat also allows the addition of a greater amount of reverts.

   b. Admits a wide range of feeds, including concentrates with a high level of impurities.
   c. Concentrates can be fed to the furnace without drying, impacting positively OPEX and CAPEX.
   d. Polymetallic concentrates containing gold and silver can also be treated with this technology, achieving high recovery of these metals.
   e. Due to its high feed flexibility and simpler preparation process, the operation has low risk of interruption, reducing maintenance and repair costs.
3. Environmental performance:
   a. Fugitive off-gases are prevented by keeping the feeding mouth under negative pressure.
   b. High impurity removal capacity.

In general terms, BBS/SKS offers a smelting process with lower investment and operational costs, suitable for treatment of a wide range of concentrates and capable of complying with high environmental standards.

Operations and projects

Besides the first commercial application of the technology that was installed in Vietnam, all the rest of the smelters operating with BBS/SKS technology are located in China. In Table 2, some of the most relevant smelters with this technology, in terms of capacity, are shown.

Additionally to current operations, several new plants are under study, design and construction. The most emblematic of these projects is the modernisation of ENAMI’s smelter, a Chilean state-owned mining company. The feasibility study has already been finished and the operation is expected to start in 2023. If completed, this smelter will be the first relevant project with the BBS/SKS technology implemented outside of China.

Table 2: Smelters with SKS technology, designed by ENFI.
Sources: Xu (2016), Xu (2018).

Smelter	Country	Capacity (kt/a conc.)	Operation start
Sin QuyinCu Smelter	Vietnam	50	2008
Dongying Fangyuan Phase I Cu Smelter	China	500	2008
Humon Cu Smelter	China	500	2010
Huading Cu Smelter in Baotou	China	450	2012
Yuanqu Cu Smelter of Zhongtiaoshan Group	China	500	2014
Yuguang Cu Smelter	China	500	2014
Zhongyuan Gold Smelter	China	1,500	2015
Dongying Fangyuan Phase II Cu Smelter	China	1,000	2015
Lingbao Copper Smelter	China	660	2018

Current and future trends

As mentioned, the complete smelting process is carried out, consecutively, in three furnaces: smelting, conversion and anode furnace. Based on the BBS/SKS smelting process, the bottom blowing continuous converting (BCC) technology has been developed. Currently, three smelters operate with the SKS-BCC smelter-conversion pair: Yuguang Cu Smelter, Dongying Fangyuan Phase II Cu Smelter, Lingbao Copper Smelter, commissioned in 2014, 2015 and 2018, respectively (Jie, 2016). Additionally, several other SKS-BCC projects are currently under study (including ENAMI's smelter in Chile). This technological set have shown promising results, achieving an efficient, continuous, operation. With the development of the new projects and the maturity of the current operations, these technologies are expected to improve to a new level the performance of copper smelters.

2.3.3 Thickened and paste tailing disposal

Mining operations produce large amounts of waste. Among these, tailings raise special concern due to their environmental footprint and potential danger to adjacent communities. Tailings are the slurry waste from the flotation process, containing water and fine-grained mined rock with small amounts of valuable minerals. Due to declining ore grades, the amount of tailings produced by the mining industry as a whole has considerably increased over the past decades, reaching rates of five up to fourteen billions tons per year (Schoenberger, 2016).

In current days, there exist several methods to dispose mine tailings, from using them as backfill in underground mines, to building on-land tailings storage facilities (TSF), or even discharge them into nearby waterbodies. On-land TSF are the most commonly used and they can be classified as conventional tailings disposal (dams built from mine waste), thickened tailings disposal (TTD), paste tailings disposal (PTD) and filtered (cake) tailings disposal. The conventional method is still the most used around the world. However, several tailings dams built under this logic have suffered serious incidents. The causes for these failures are usually the poor control of water balance, lack of consistency in the construction and the low safety standards in the operation (Edraki et al., 2014). Among recent events, the most dramatic cases may be the Samarco dam disaster on November 5, 2015 in Mariana, Minas Gerais, Brazil, and the Brumadinho dam failure on January 25, 2019 in the surroundings of Brumadinho, Minas Gerais, Brazil. Both tailings dams were associated with iron ore mines, operations owned by BHP (50%) and Vale (50%) in the first case, and Vale (100%) in the second one. Approximately 60 million cubic meters of tailings were released in Samarco's event and 12 in Brumadinho. Besides the enormous impact on the environment, these disasters left 19 and 237 fatal victims, respectively[8].

Increasing environmental awareness and recent catastrophic incidents in conventional tailings disposal, like the ones previously described, have led the industry to look for other, safer disposal methods over the last decades. Since failures happen either by a breach in the confining embankment or the release of liquefied tailings, TTD and PTD represent viable solutions for preventing the liquefaction of tailings, and therefore, reducing the risk of an extensive release of material in case of a breach in the confining embankment (Jewell, 2016). The adoption of these technologies became more frequent from the beginning of 2000's onward. Safety reasons might often be the main driver for implementing

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[8] Information regarding dam failures retrieved from press reports.

thickening tailings processes, but also the availability or cost of water at the mine site can be an important motive for the dewatering of tailings and water recycling.

General description

The potential of liquefaction decreases with a higher solids content in the slurry. This can be achieved by removing the water before the disposal of the tailings through a thickening process. As shown in Figure 10, depending on the extend of thickening, the tailings will be classified as slurry, thickened, paste or filter cake. While thickener equipment is used to produce thickened and paste tailings, filter cake is obtained from filters, such as press or disc filters, among others. Also, a combination of thickeners and filters can be used. Filter cake tailings represent the safest option, being very unlikely to liquefy. However, thickening costs also increase while moving towards higher solids contents (Jewell, 2016).

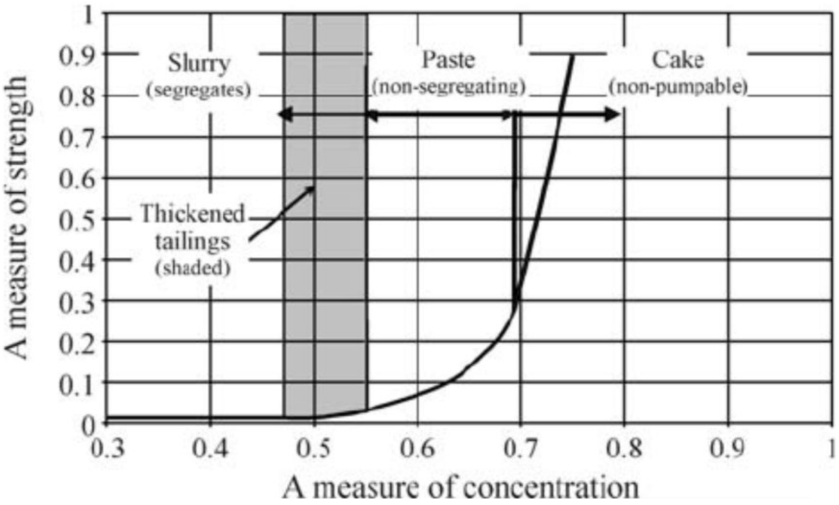

Figure 10: Effect of thickening tailings.
Taken from Jewell, Fourie A. B., and Lord (2002).

A typical deep cone thickener equipment, to obtain thickened and paste tailings, is shown in Figure 11. The thickener functioning is based on the slow rotation of its scraper blades, or rakes, over the bottom of the cone, moving the settled material to a central discharge (Figure 12). In the case of paste tailings, the thickening process can be carried out in two sequentially connected thickeners (Monardes, 2016). Nowadays, alternative equipment, such as hydrocyclones or centrifuges, are also being considered for tailings thickening processes (Klug, Rivadeneira, & Schwarz, 2018; López, 2016).

Figure 11: Typical deep cone thickener.
Taken from Serbon, Mac-Namara, and Schoenbrunn (2016).

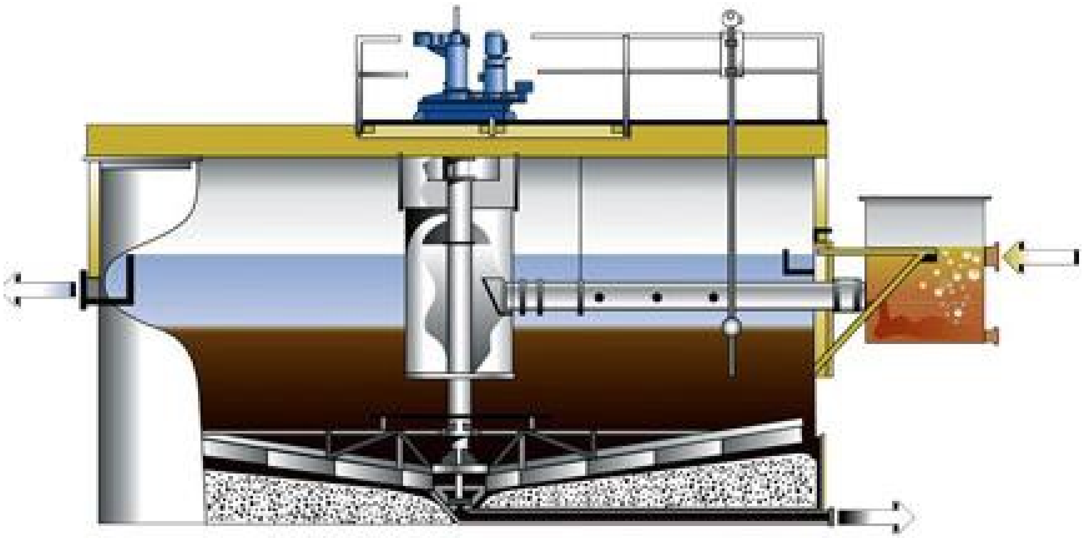

Figure 12: High capacity thickener.
Taken from Klug et al. (2018).

At the present time, TTD and especially PTD, represent more sustainable, safer and economic solutions for the disposal of tailings. Every day, more mining companies are adopting these technologies in order to ensure a sustainable future for their operations. The main features are described in the following section.

Main features

Through the TTD and PTD methods, homogeneous and self-supported tailings are produced. These, offer a series of benefits, which main ones are described as follows (Edraki et al., 2014; Galaz, 2011; Schoenberger, 2016):

1. Mechanical properties of thickened and paste tailings allow them to be disposed with a steeper beach slope. Therefore, the surface requirement is lower than conventional tailings disposal, reducing environmental footprint and increasing storage capacity of the TSF. Also, smaller embankments are required (see Figure 13).
2. High seismic stability and low or null liquefaction risk.
3. High water recovery in thickening process, thus reducing consumption of water from other sources in the mining processes. Especially important in zones with water scarcity or high water prices.
4. Low risk of groundwater pollution.
5. Reduction of energy consumption for water pumping from TSF.

Thickening processes also involve additional investment and operational costs. However, it can be cost-effective when considering the risk of a failure in a conventional TSF and the associate high costs, direct and indirect (reputational, social license to operate) (Jewell, 2016). Moreover, given the current situation of environmental awareness, stricter regulations, surface and water scarcity, these disposal methods are often the only viable alternative, situation that is expected to be intensified in the future.

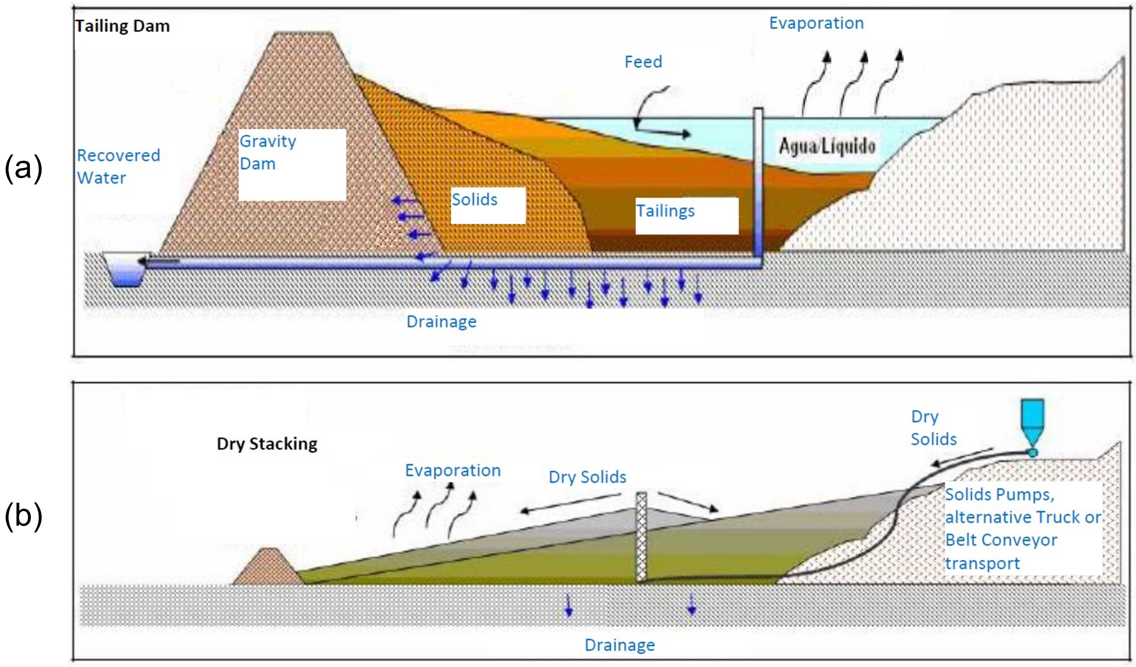

**Figure 13: Conventional tailings disposal (a) vs. PTD (b).
Taken from Klug et al. (2018).**

Operations and projects

TTD and TPD projects have been developed in many countries around the world over the past decades. As shown in Figure 14, by 2016 at least 66 TSF were operated under one of these methods, and several other were under evaluation or construction.

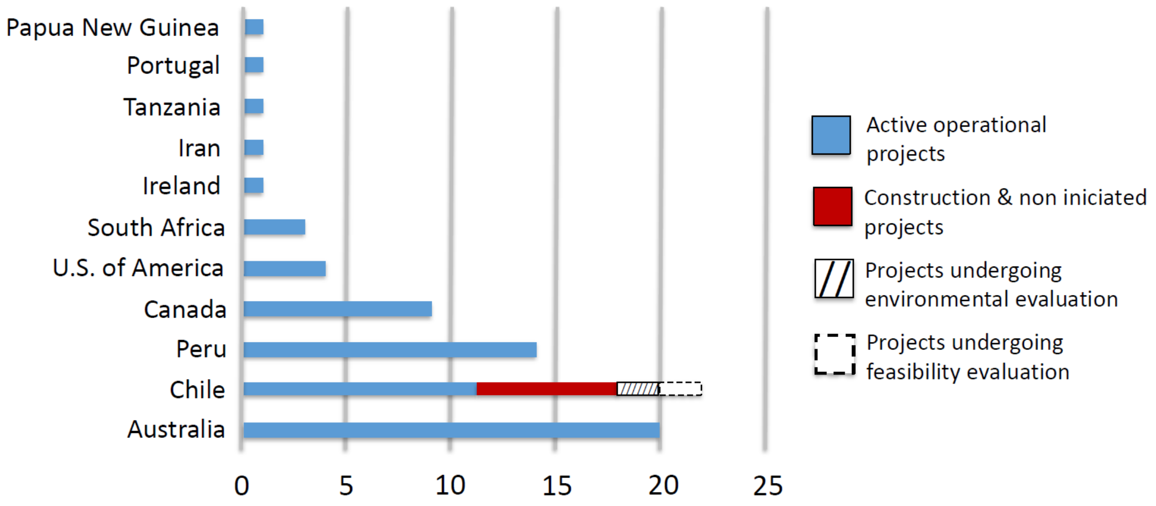

**Figure 14: Amount of TTD and PTD by country, in 2016.
Taken from Espinace, Villavicencio, and Fourie (2016).**

Current and future trends

It is appropriate to expect that for their environmental impact and potential danger for communities, especially after recent tragedies in Brazil and other places in the world, conventional tailings disposals will be soon no longer accepted as a TSF. At the same time, the conditions of surface and water scarcity are not expected to change, on the contrary. For these reasons, TTD and PTD have become the most attractive alternatives and most likely their adoption will continue to increase.

However, there are some challenges that need to be handled. On the side of authorities, regulations need to be updated in order to properly cover the specific issues related to these tailings disposal methods. Whereas the companies must overcome some of the difficulties experimented along the years of operation of these TSF, improving their design by incorporating the learned lessons. Also, the lack of trained personnel must be address, for which public-private collaboration initiatives can be developed (Espinace et al., 2016; Strömberg, July 5, 016).

2.4 Summary

In this chapter, the importance of innovation in the mining industry has been analysed, as a crucial factor in the improvement of labour productivity through past decades. Though its importance, mining companies usually show low levels of R&D intensity, similar to mature industries and far from high-tech sectors. The tendency to vertical disintegration has led firms to focus on their core business, relying mainly on equipment manufacturers and suppliers for the development of innovative solutions. Also, collaborative alliances between mining companies, suppliers and research centres share participation in the development of new technologies. Accordingly, over the past 120 years, only one to four revolutionary technologies have been developed in each commodity sector, considered by separate.

Recent innovations include the adoption of preconditioning techniques, new smelting technologies (BBS/SKS) and thickened tailings disposal methods (TTD/PTD). While preconditioning has allowed the operation of deep mines in high-stress environments, the BBS/SKS furnace emerged as a productivity-driven development, enhancing the efficiency of smelting processes. By their side, TTD and PPD offer sustainable, safe and cost-effective solutions for the disposal of mine tailings, within an increasingly environmentally concerned and empowered society, allowing to project the continuity of the mining activity in the future.

3 Current trends and mining of the future

Defining a future view for an industry is not a simple task. Nowadays, the world is changing faster than ever before. New technologies are developed every day, impacting the way of living of people. The phrase, “we live in a different world than the one where our parents grew up”, doesn’t completely cover the reality of the past few decades. For example, in current days most people wouldn’t conceive their lives without their smartphones, and even though the first ones were commercialised in 1992, the massification of these devices came only a little more than a decade ago (e.g. the first iPhone was developed in 2007).

Nevertheless, in the case of the mining industry it is possible to identify certain trends that can be of help to outline this future scenario. First and most evident, it is the major technological shift occurring across all industries: the so-called Fourth Industrial Revolution, or simply Industry 4.0, as the transition to the digital era. Then, social and environmental concerns are already compelling mining to look for safer, more efficient and sustainable ways of conducting the business. Reduction of energy and water consumption, lower emissions and waste generation, are all factors that will be in the core of the “mine of the future”.

In the first part of this chapter, the implications of Industry 4.0 for the mining sector are reviewed. Specifically, the concept of digital transformation and the set of technologies that it involves, along with the current status of progress of its implementation across the industry and its challenges. In the second part, a series of other relevant trends that will likely shape the future of the industry are discussed, such as electromobility, invisible zero-waste mining and continuous mining.

3.1 Digital transformation in mining

Over recent history and since the beginning of industrialisation, several changes in production paradigms have taken place, promoted by the surge and application of novel technologies. As shown in Figure 15, the world has already seen three paradigm shifts, better known as industrial revolutions. Currently, a new transformation is in progress from the hand of cyber-physical systems and a set of new technology developments, e.g. automation, internet of things and analytics (Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014; Rüßmann et al., 2015).

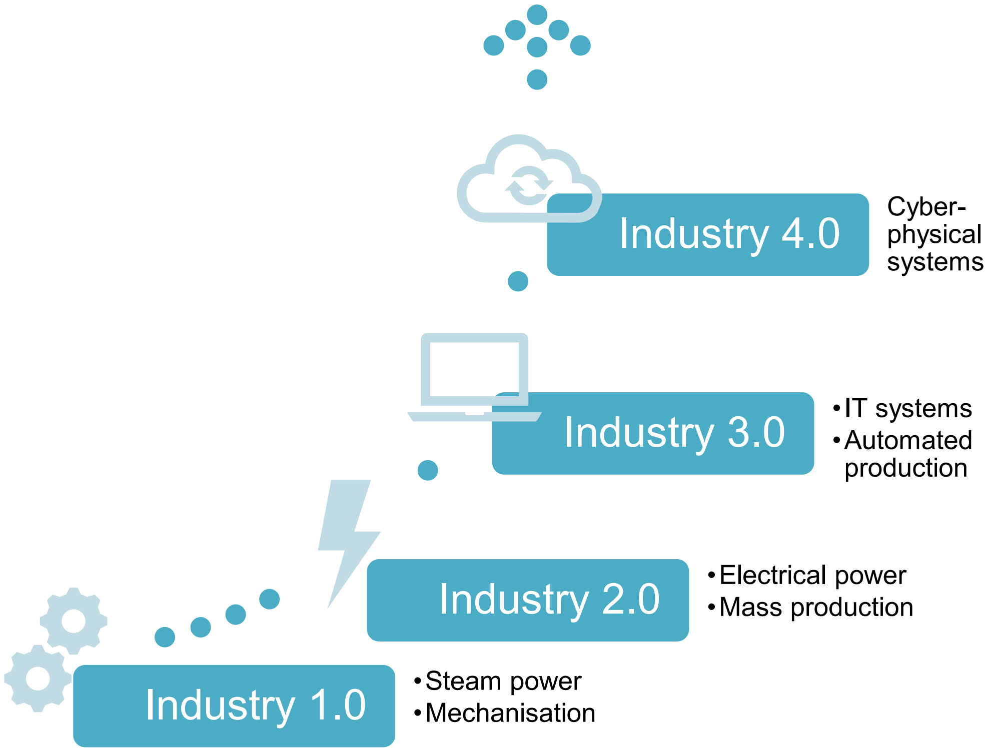

Figure 15: Industrial revolutions.
Source: Own elaboration.

The Fourth Industrial Revolution brings a new concept of industry, also called Industry 4.0. This concept is based on an advanced digitalisation of production processes and the combination of internet-oriented technologies, allowing the connection between smart sensors, machines and IT systems across the value chain. The implementation of these cyber-physical systems should bring a series of benefits, such as productivity increase by the automation of production and decision-making processes, reduction of waste, improvement of equipment utilisation and maintenance costs reduction. However, Industry 4.0 is not only about the adoption of new technologies, but it will also demand organisational changes, specialised knowledge and expertise (Lasi et al., 2014; Rüßmann et al., 2015).

To achieve the scenario set by Industry 4.0, companies from all sectors, though at different speeds, are implementing the necessary changes at a technological and organisation level. These changes constitute the process of digital transformation, which is described and analysed in the following sections.

3.1.1 What is digital transformation?

Though the term digital transformation (DT) has been extensively used in recent years, mainly to describe the adaptation process of organisations to new digital technologies, there is no a unique definition for it. On the contrary, there are many. Acknowledging this situation, and after an exhaustive review of DT-related literature, Vial (2019) offers the following definition: *”a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies*”.

The reason for the existence of various acceptations for DT may lie in the differences among industries: each sector operates in particular ways, therefore each digital technology will have a different impact, depending on the industrial sector adopting it.

The specific information, computing, communication and connectivity technologies involved in DT also varies from one industry to another. In the case of mining, however, it is possible to identify a set of tools that will and are already affecting the processes not only at the mine site, but across the operational and corporate units within a firm.

3.1.2 Key technologies in the digital mine

DT is a transversal process of change across the complete value chain of the mining industry, from the exploration to the production of final products, their commercialisation and even the closure of operation sites. Experts, companies and government agencies have been discussing how the “digital mine” should look like, while advancing forward in the DT process. Deloitte (2017) offers an illustrative and representative view of the effects of this transformation in the mining business (Figure 16), and how the modern digital technologies will enhance and change each one of the stages of the value chain.

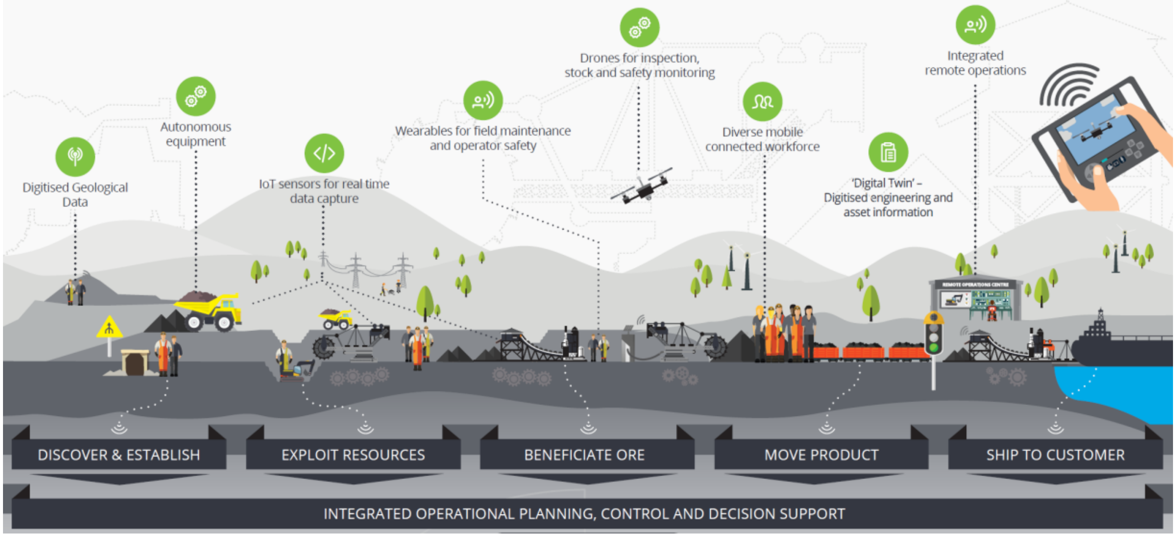

Figure 16: Deloitte's view of the digital mine.
Taken from Deloitte (2017).

A more detailed scheme is the one presented by Coombs, O'Donnell, Sparks, Veiga, and Jones (2019) at the World Copper Conference 2019, in Santiago, Chile (Figure 17). This scheme represents the shared view of organisations with a high level of knowledge and expertise in the industry, such as CRU Consulting, Wood PLC, Anglo American and APRIMIN[9].

As shown, novel technologies are producing operational changes across the value chain, and their use is not necessarily exclusive for a specific activity. For example, intelligent operation centres are being implemented for both, extraction and processing operations. Likewise, augmented and virtual reality, along with digital twinning are tools that will enhance the design and construction of mining projects (“Establish” in Figure 17), and the extraction and processing operations.

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[9] Association of Industrial Suppliers for Mining (Chile).

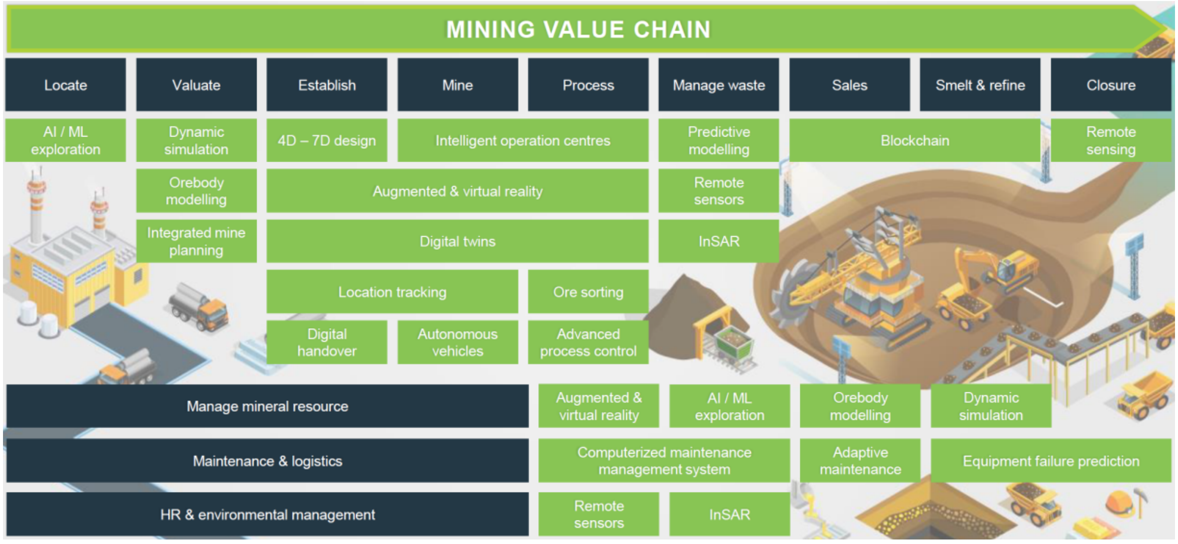


Figure 17: DT technologies in the different stages of the mining value chain. Taken from Coombs et al. (2019).

While the view of the “digital mine” may vary among firms an organisations, it is possible to define a set of core technologies that represent the pillars of the DT in the mining industry (Bonomelli, 2018; Canart, 2018; Coombs et al., 2019; Deloitte, 2017; Espinoza, 2018; Pino, 2018; Romano, 2018; Sganzerla, Seixas, & Conti, 2016; World Economic Forum & Accenture, 2017). These key elements are described below:

Automation, robotics and remote operation

These technologies might hold the highest level of implementation among the tools offered by DT. The first and more clear benefit of the automation of processes, use of robots in critical activities and remote operation centres (ROC) is the improving of safety, by reducing the number of operators required in hazardous sites (Sganzerla et al., 2016).

ROCs can also reduce significantly OPEX and CAPEX of mining operations. Since less workforce is needed at the mine site, fewer or none supporting infrastructure is required, such as housing installations, hospitals or schools. Also, other expenses are reduced, such as transportation of operators. The impact on costs is larger as the location of the mine is more remote, distant an isolated (Sganzerla et al., 2016).

The use of autonomous equipment, such as hauling trucks, LHDs and drillers is expanding rapidly. For example, global equipment manufacturer Caterpillar has provided more than 239 autonomous trucks for large-scale mining operations in Australia, Brazil, Canada and the U.S., as shown in Figure 18.

Country	Customer	Mine Site	Model	Material	Year	N° of Trucks
USA	BHP BILLITON	NAVAJO	793	---		
AUSTRALIA	FMG Fortescue	SOMOLON	793F	Iron Ore	2013	70
AUSTRALIA	BHP BILLITON	JIMBLEBAR	793F	Iron Ore	2013	50
BRASIL	XX	XXX	793F	Iron Ore	2016	XX
CANADA	IMPERIAL OIL	KEARL	797F	Oil Sand	2017	XX
AUSTRALIA	FMG Fortescue	CHICHESTER	793F 930E-4 789D	Iron Ore	2018	100
AUSTRALIA	RIO TINTO	MARANDOO	793F	Iron Ore	2018	19
CANADA	XX	XX	793F	Copper	2018	XX

Figure 18: Mining operations using Caterpillar autonomous trucks.
Taken from Mosqueira (2019).

Similarly, Komatsu holds a total fleet of 141 autonomous trucks distributed in Australia, Canada, Chile, Japan and the U.S. In Chile, these trucks operate in Codelco's mine Gabriela Mistral. Over the 10 years of operation of the mine, the use of autonomous trucks has allowed a significant collision risks reduction and high levels of productivity and tires performance (Canelo, 2018).

In general terms, besides the benefits in safety, autonomous equipment enhance productivity and reduce operational costs, by increasing equipment's utilisation (due to the continuous operation), reducing variability in the production outcome and improving tires and components performances (Canelo, 2018; Deloitte, 2017).

Internet of Things (IoT), smart sensors / real-time data capture

IoT is understood as a network of physical objects, such as sensors, equipment, machinery, and other sources of data. The elements connected to this network can then interact, exchange information and act in a coordinated way (Jeschke, Brecher, Meisen, Özdemir, & Eschert, 2017). Thanks to advances in IoT technology, nowadays it is possible to stablish low cost networks. Additionally, the development of smart sensors allows real-time capture of data from machines and equipment across the operation. This generation of data is the base to conduct an integrated planning and control, considering the different units within the operation, and support the decision-making process (Deloitte, 2017).

Analytics, Artificial Intelligence (AI) / Machine Learning (ML)

Due to the digitisation of processes, advances in IoT and real-time data capture, mining operations have enormous amounts of data available regarding production, processes, performance of machines, among others. Through advanced analytics methods it is possible to transform this information allowing its use for a better planning of activities and to support fast and effective decision-making processes for the operation. Predictive models can also be developed to enhance maintenance of equipment, and therefore, improving productivity (Bonomelli, 2018).

AI/ML methods are also being applied for mineral prospecting (Carranza & Laborte, 2015; Chen & Wu, 2017; Rodriguez-Galiano, Sanchez-Castillo, Chica-Olmo, & Chica-Rivas, 2015). It is expected that these methods will optimise the prospection and exploration activities, reducing costs and improving their accuracy.

Digital twinning

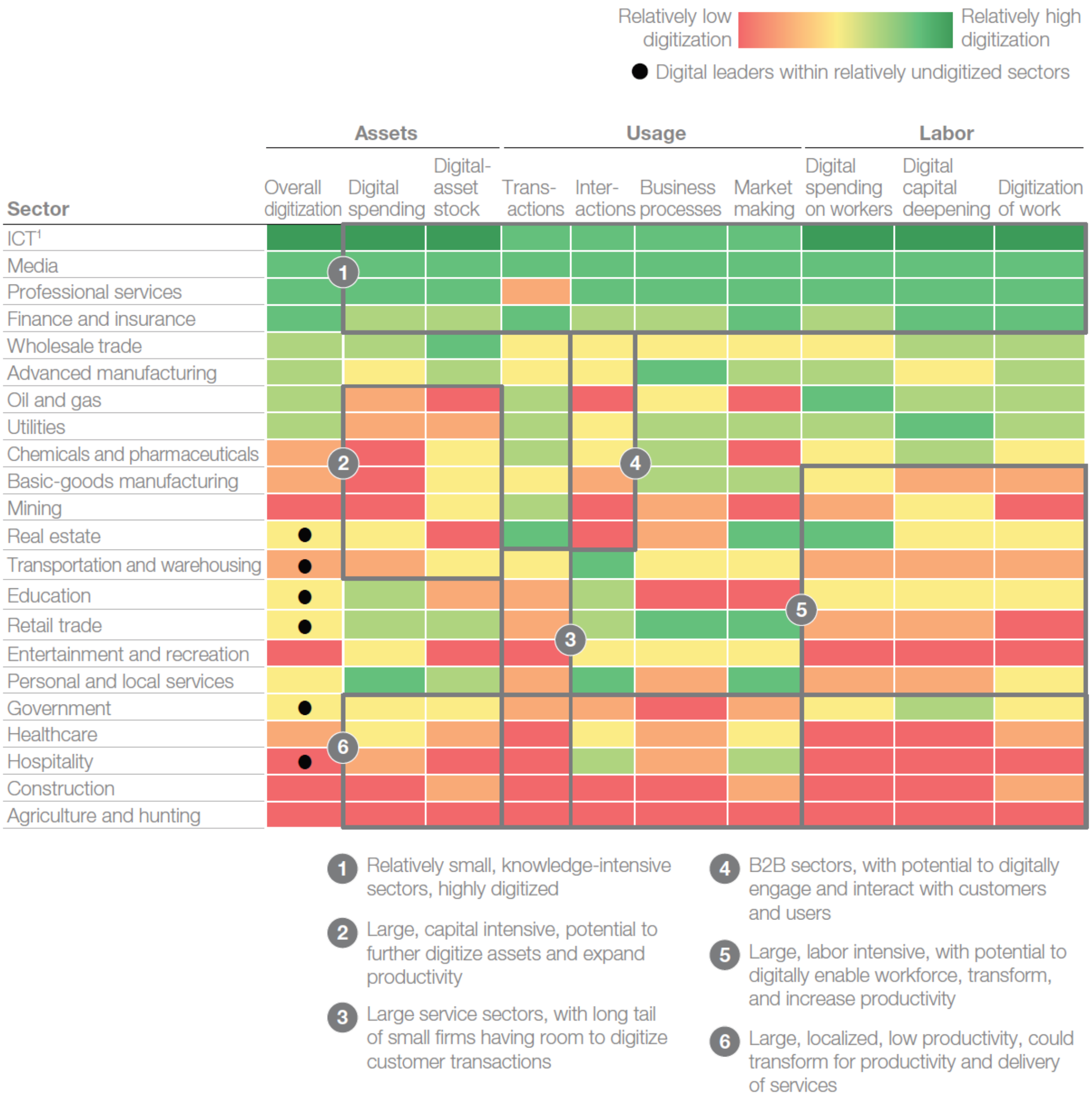
The concept of digital twinning refers to the construction of a digital model of the physical operation. This is possible using the geological and engineering information of the site, but more importantly, thanks to the real-time data generated from the sensors connected across the operation. With the digital twin of the mine, it is possible to perform simulations, predict potential failures or downturns in equipment performance. Thus, the digital twin constitutes a useful tool to improve operational planning and reduce operational costs, by avoiding unexpected interruption in production processes and optimising the maintenance of equipment (Bonomelli, 2018; Deloitte, 2017).

3.1.3 Current status of DT in the mining industry

In its study of 2017, the World Economic Forum and Accenture estimated a potential benefit for the mining industry, as consequence of DT, of US$ 190 billion over the period 2016-2025, equivalent to approximately 9% of the industry's profit (World Economic Forum & Accenture, 2017). Correspondingly, as shown in Figure 19, using the U.S. situation as an example, the mining industry has been included among the group of sectors with potential to increase productivity from the further digitisation of its assets, costumer relations processes and transformations in its workforce (Manyika, 2017). These expectations are aligned with the results of a survey conducted by Accenture in 2014 among executives from 151 mining companies around the world. In this, 85% of the surveyed executives reported that their companies were strongly supporting internal DT initiatives, and 90% that the DT programmes were already elevated into strategies and high-level decision-making (Sganzerla et al., 2016).

However, in the same Figure 19 it is possible to appreciate the low level of overall digitalisation of mining, when compared to other industries. By 2014, though DT was mentioned in six out of ten of the largest (by market value) global mining companies' annual reports, qualitative benefits from DT were reported only by three of them and only one presented actual quantitative gains (Sganzerla et al., 2016). This confirms that, though DT has claimed a relevant position among mining companies' concerns, in average, the industry is still in the early stages of this transformation, and most of the potential benefits are still to be unlocked.

Likewise, a survey conducted on 25 companies from the knowledge intensive mining supplier sector in Chile, revealed that 60% of them perceives a medium level of interest from the mining companies to incorporate DT-related technologies, and 40% a low level of interest. None of the surveyed firms perceives a high level of interest from mining companies to incorporate these technologies in their operations. Regardless, most of these suppliers are already developing or will develop in the next five years products or services with technologies 4.0, being automation, analytics and smart sensors the most frequent ones (COCHILCO, 2018).



① Relatively small, knowledge-intensive sectors, highly digitized

② Large, capital intensive, potential to further digitize assets and expand productivity

③ Large service sectors, with long tail of small firms having room to digitize customer transactions

④ B2B sectors, with potential to digitally engage and interact with customers and users

⑤ Large, labor intensive, with potential to digitally enable workforce, transform, and increase productivity

⑥ Large, localized, low productivity, could transform for productivity and delivery of services

Figure 19: Extent of digitisation by sector. McKinsey Global Institute Digitisation Index – U.S. example. 2015 or latest available data.
Taken from Manyika (2017).

In general terms, though DT is frequently mentioned as one of the main concerns among most of large-scale mining companies, which over the years has generated great expectations regarding its benefits, the level of digitisation of the industry remains low. Nevertheless, some technologies present a greater level of adoption than others. For example, autonomous and semi-autonomous equipment, such as trucks, LHDs, drills and trains started to be tested more than a decade ago (in some cases, even before); some have been successfully operating for several years now, and are rapidly spreading (Canelo, 2018; Gustafson, 2011; Mosqueira, 2019). Likewise, several companies have implemented ROCs to control their operations remotely. In Chile, for example, Codelco has a ROC for its mine Ministro Hales and it is developing centres for three more of its divisions (Parada, 2018). BHP is also currently implementing its Centre of Integrated Operations (CIO) in Santiago, Chile, from which it will coordinate all its operations in the region[10].

Smart sensors and monitoring systems are also already generating large amounts of data. However, the wide and successful application of advanced analytics to support and gradually automate the operational decision-making processes is still to come. Today, its use remains mainly in the construction of predictive models for maintenance purposes and the visualisation of data to support human decision-making.

3.1.4 Challenges in the implementation of DT

For the period 2019-2020, EY (2018) has identify the "digital effectiveness" as the second most relevant risk for the mining industry. It highlights the importance of advancing in digitisation, as a necessity for companies to remain competitive. The main risk lies then on the fact that DT is often perceived as a task exclusive of the information technology (IT) area. Nonetheless, to achieve a truly effective and value-creative transformation, it must be carried out as a joint task across the organisation, with a shared view of the business goals and a strong commitment from the top management. Otherwise, DT initiatives will remain as isolated IT projects, with no significant benefits considering the investments involved (Canart, 2018; Espinoza, 2018; EY, 2018).

Ensure the convergence of IT and OT (operational technology) is also key for a successful DT. These areas have traditionally worked by different paths: IT closely to corporate and support systems, while OT running core processes at the operation site. However, the automation of processes requires an integrated IT/OT management (Deloitte, 2017).

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[10] Information provided through personal communication.

DT is a process of change that goes beyond technology. As mentioned in the first paragraph of this section, it requires coordination across the whole company. But it is also important to understand what this transformation will mean at an organisational level (Canart, 2018). Structures will suffer changes by the automation of processes and introduction of new technologies and methods. This situation must be considered and evaluated. The new structures must be design in advance and action must be taken to prepare the employees for these new arrangements. New knowledge and skills will be required, so the firms should also invest in the proper training programmes to face DT.

Finally, in an increasing digital environment, a special focus must be put in cybersecurity. DT brings a wider connectivity among equipment and sensors, but also between different business units. The company could then be expose to greater risks of security breaches. For this reason, cybersecurity constitutes a fundamental element in DT (Deloitte, 2017; Sganzerla et al., 2016). In fact, EY (2018) also classified this issue as the fourth most important risk for the mining industry in 2019-2020. To overcome this risk, a solid "cybersecurity culture" must be promote in every level of the organisation, incorporating new security-related practices in the daily responsibilities of the employees, along with the measurement of relevant KPIs and a periodical revision of the adopted strategies to evaluate their effectiveness and generate improvements, if necessary (EY, 2018).

3.2 Mining beyond digital transformation

In parallel with the technological wave brought by the digital transformation, a series of other trends have been gaining relevance in the mining industry over recent years. Driven by safety and environmental concerns, costs reduction, enhancement of efficiency and productivity in the operation, or a mix of these motives, these trends are complementary to the technologies 4.0 and offer an idea of the future paths that mining might follow.

In this section, three important trends are described and analysed. Specifically, electromobility, invisible zero-waste mining and continuous mining.

3.2.1 Electromobility

Electromobility, as the development and use of electric-powered vehicles, is a technological trend across industries. From personal-use cars and public transportation vehicles, to heavy machinery, electromobility offers an economical and more environmentally friendly alternative to the use of fossil fuels.

Mining is especially affected by this paradigm change. Most of mobile equipment in mining operations has been historically powered by internal combustion engines (ICE), using diesel fuel. While the impact of the negative aspects of these engines might be bearable in open pit operations, in underground mines, where ventilation can account for up to 25%-40% of the total energy costs, the situation is different (Erdtmann, 2018). Diesel ICE emit exhaust gases containing a series of pollutants, such as unburned hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx) and diesel particulate matter (DPM). Additionally, a large amount of heat is also produced. All these elements increase the demand for fresh air flow in order to ensure a proper working environment for operators and equipment, having a significant impact on costs (Varaschin & Souza, 2015).

Moreover, due to the increasing environmental and safety awareness in the industry, regulations regarding the admissible levels of pollutants have become stricter in the past decades and are likely to become even stricter in the future. At the same time, after exhausting shallow deposits mining is moving to deeper locations, aggravating the temperature conditions (Paraszczak, Svedlund, Fytas, & Laflamme, 2014).

Even though some methods to provide electric power have been used for a long time already (e.g. trolley assist), today there are more incentives to look for electric-powered alternatives to replace the mobile equipment that have been predominantly running with diesel ICE, like LHDs and haul trucks. According to the method used to supply the motor with electric energy, this equipment can be classified into five categories (Paraszczak et al., 2014):

- Trolley-powered.
- Battery-powered.
- Cable-powered.
- Hybrid ICE/electric equipment.

- Hydrogen fuel cell-powered

In Table 3, a summary of the differences among diesel-powered equipment and the categories mentioned of electric-powered equipment, according to key operational, environmental and economic parameters, is presented.

Table 3: Comparison between diesel-powered and electric-powered equipment.
Sources: Paraszczak et al. (2014), Valicek and Fourie F. (2014), Varaschin and Souza (2015).

Parameter	Diesel	Battery	Cable	Trolley	Hybrid	Hydrogen
Flexibility	High	High	Low	Low	High	High
Autonomy	High	Low	High	High	Medium	High
Specific energy	High	Low	High	High	Medium	High
Energy efficiency	Low	High	High	High	High	High
Overload capacity	Low	High	High	High	High	High
Additional infrastructure	No	No	Yes	Yes	No	Yes
CAPEX	Low	High	High	High	High	High
OPEX	High	Low	Low	Low	Low	Low
Maintenance requirements	High	Low	High	Low	Low	Low
Service life	Low	High	High	High	High	High
Refuelling/recharging	Fast	Slow	None	Fast	Slow	Slow
Pollutants emission	High	None	None	Low	Low	Low
Heat generation	High	Low	Low	Low	Low	Low
Noise and vibration	High	Low	Low	Low	Low	Low

In general terms, the main advantages of electric-powered over diesel-powered equipment are higher energy efficiency, higher service life (and therefore, lower fleet requirements along the life of the mine), lower maintenance requirements, reduced generation of pollutants, heat and noise, and overall lower operating costs. The lower ventilation requirements can also have an impact on the CAPEX of the mining project, by reducing the size of ventilation adits and fans. On the downside, electric-powered equipment usually present higher CAPEX and depending on the type, can present some other disadvantages (as presented in Table 3). Also, the specific conditions of the operation can affect the preference for one specific technology. E.g. open pit vs. underground, haulage distances, deepness and rock temperature, regulations of the country, diesel and electricity prices, etc. For these reasons, an integral techno-economic evaluation must be conducted in each case.

Nevertheless, a lot of effort is currently being put in R&D regarding electric-powered equipment, especially battery and hydrogen fuel cell-powered. These show the greater potential to replace diesel equipment, due to their high flexibility, besides the safety and environmental advantages already mentioned (Erdtmann, 2018).

Though the transition to electric mining equipment has been relatively slow, results difficult to think of a mining industry of the future still depending on fossil fuels. The shift to cleaner sources of energy is global: industries and governments across the world are implementing renewable energy sources strategies and policies, regulations become stricter and social scrutiny harder. Electromobility has arrived to stay and the mining industry it is not excluded from its influence.

3.2.2 Invisible zero-waste mining

The concept of a mining with no impact on the surface is not new. Underground operations have been using their waste material to backfilling open cavities left after ore extraction, mainly for stability reasons and as a mean to reduce haulage costs. At the same time, this practice reduces subsidence effect, and therefore, the impact on the surface above the underground mine. However, it is not possible to use all the waste extracted due to interference with the operation (e.g. during early development stages). Also, not every mining method allows backfilling application (e.g. caving operations). Therefore, it is certain that impact on the surface can be significantly reduced, but most of the times it is unavoidable.

In this regard, in situ leaching (ISL), also referred as in situ recovery (ISR), constitutes an alternative that minimise the effect on surface and generates practically zero waste. This method is understood as the in-place leaching of the ore, recovery of the enriched solutions and transportation of them to the surface for further processing. A general scheme is shown in Figure 20.

ISL has been mainly applied in uranium mining (since it was first introduced in 1959 in the U.S.). There is also record of successful cases of ISL applied in copper and gold deposit, though in relatively small scales. Besides typical characteristics of deposits (e.g. shape, dimensions, mineralisation, grade distribution, etc.), the most critical factors restricting its applicability are permeability, hydrogeological conditions in site and the possibility of achieving selective leachability of the ore body (Seredkin, Zabolotsky, & Jeffress, 2016). The containment of the leaching solutions within the zone of interest to prevent the contamination of groundwater, might be the greatest environmental risk regarding ISL (Sinclair & Thompson, 2015).

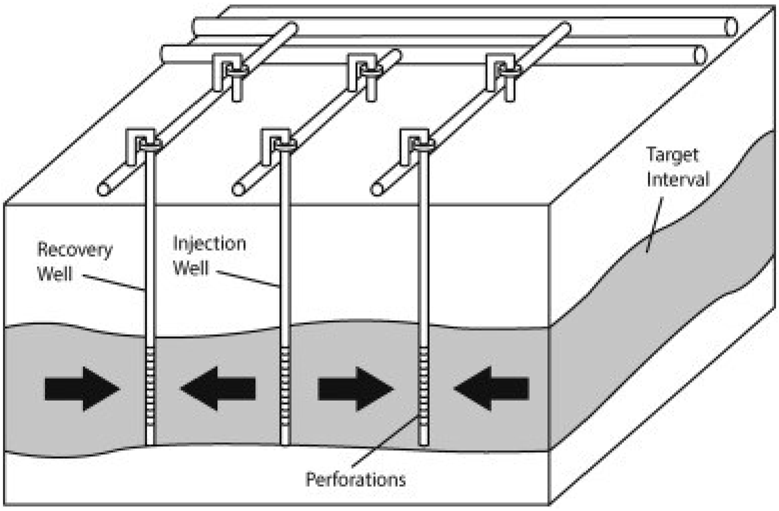

Figure 20: Idealized diagram of an in situ leaching system for intact material. Taken from Sinclair and Thompson (2015).

From an economic point of view, ISL presents obvious advantages over traditional mining methods. Energy consumption is reduced, thus lower OPEX need to be met. ISL also requires lower CAPEX for infrastructure and mine developments. Additionally, this mining method admits a high production flexibility and can be developed as a modular project, if desired (Seredkin et al., 2016).

Future widespread application of ISL depends greatly in the technological advance regarding permeability enhancement and hydrogeological management. Findings in preconditioning techniques used in caving operations are likely to be adapted and applied in ISL mining for permeability improvement. Whereas the use of barriers, such as the gel barriers widely used in the oil and gas industry to control the flow of sweep and production, are also potentially applicable for this mining method as a tool for proper leaching solutions containment (Batterham, 2017). For these reasons, R&D efforts should be mainly aimed to the adaptation and improvement of existing technologies.

Besides environmental benefits of this method, if the restrictions mentioned can be overcome, ISL opens the possibility to exploit very deep low-grade deposits, currently uneconomic or technically unfeasible to mine.

3.2.3 Continuous mining

Continuous mining is not a new concept: continuous extraction and material handling systems have been used for many years in the coal mining industry. In surface operations, this has been carried out combining the action of bucket wheels excavators for the extraction and conveyor belt systems for the transport of coal and waste. Meanwhile, underground methods such as longwall mining and room and pillar (by using continuous miner equipment), have also offered continuous flows of material. However, due to rock strength, most of metallic ore deposits don’t allow mechanical extraction methods, making necessary the use of drill and blasting, and therefore, impeding continuous operation.

Traditional mining methods combining drill and blasting, excavators for loading and mobile equipment for hauling (or LHD for loading and hauling, in underground mining), have high levels of operational inefficiency and low equipment utilisation: significant hauling cycles, in which at least half of the time the mobile equipment is empty, along with queues and waiting times at loading and dumping site, are some of the inefficiencies of these processes.

As discussed in previous sections, increasing productivity and enhancing efficiency of operations are main drivers for innovation. Then, the development of continuous extraction and material handling systems, outside the coal sector, are trends that will likely gain importance in the near future.

Indeed, efforts in this matter have already been done in recent years. One example is the S11D iron mine of Vale in Brazil. This mine operates in four independent truckless systems. Each system consists of an excavator, a mobile sizer rig (MSR) and a mobile belt wagon (MBW) that connects to a belt conveyor (BC), as shown in Figure 21. Due to its continuous truckless design, the project has reported high operating productivity rates (about four times higher than Vale’s typical rates in the region) and lower operating costs (approximately three times lower than Vale’s traditional cost levels in the region) (Scheepers, 2018).

**Figure 21: System 1, Vale's S11D mine in Brazil.
Taken from Scheepers (2018).**

Initiatives in underground mining have also been developed. Such is the case of the Continuous Mining System (CMS) for caving operations, introduced by Codelco in Chile (Figure 22). This design considered the continuous and simultaneous extraction of broken ore from active drawpoints in a block or panel caving mine, by the combined action of feeders (located at the drawpoints), heavy weight conveyors and primary crushers (Orellana, Castro, Hekmat, & Arancibia, 2017).

After almost twenty years of research and testing, the project was finally dismissed as a consequence of difficulties faced in the construction phase for its industrial validation (Codelco, 2018b). Thus, the design didn't get to be tested at an industrial level, and therefore, its real potential and applicability remained unclear. However, previous tests and studies suggested that great benefits in terms of productivity, costs, workforce requirements and ramp-up duration can be achieved through the implementation of the CMS (Baraqui, 2014).

The CMS project is presented and analysed in detail in chapter 4.

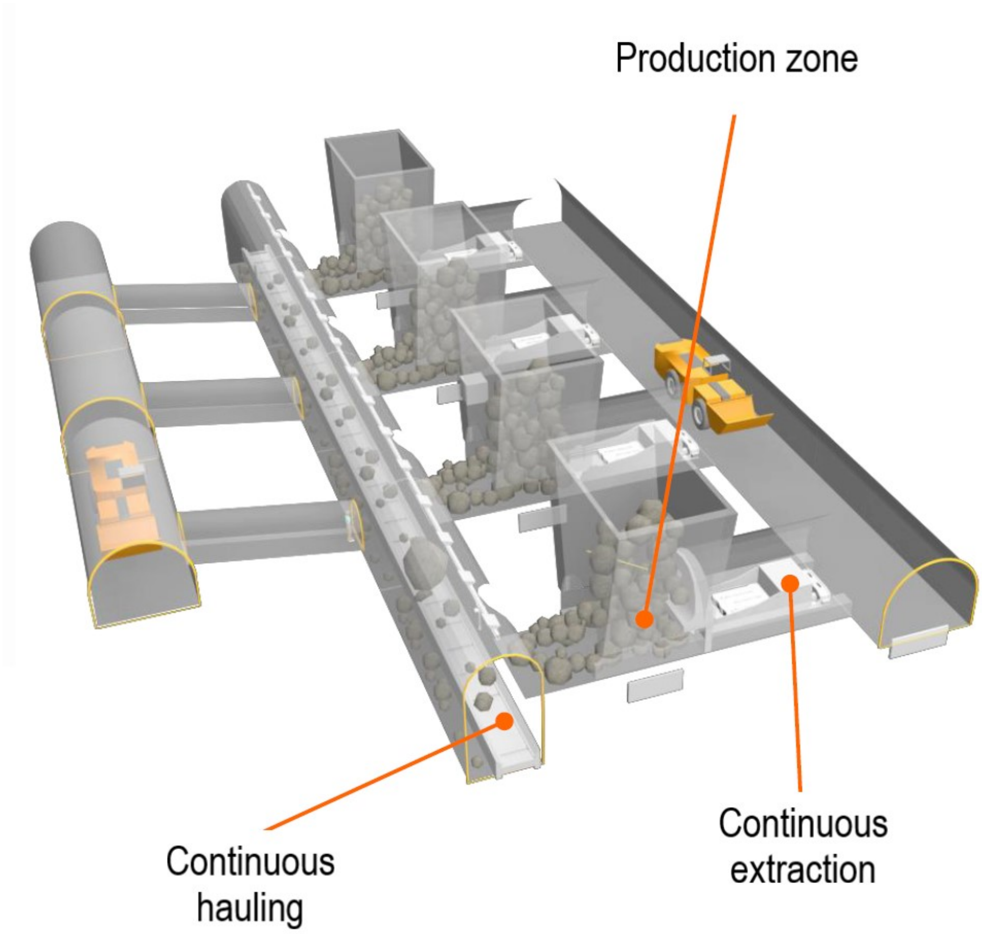

**Figure 22: Continuous Mining System (CMS) concept of Codelco.
Taken from Baraqui (2014).**

4 Case study: A continuous mining system for caving operations

The Continuous Mining System (CMS) was an innovation project developed by Codelco, in Chile, that intended to create a continuous material handling system for block and panel caving operations. With the objective of illustrating the impacts and implications of implementing a step change innovation project, the CMS initiative is described and analysed in this chapter.

4.1 Codelco

Codelco is a Chilean state-owned mining company, first copper and second molybdenum worldwide producer. It is divided in eight operating divisions located in the central and north of Chile. Its headquarters (Casa Matriz in Figure 23) are in Santiago. In total, Codelco possess seven mining operations, four smelters and three refineries (Codelco, 2018a).

Figure 23: Location of operations and headquarters of Codelco.
Source: https://www.codelco.com/

Divisions Andina, El Teniente and Salvador include panel caving operations. Thus, the importance of projects such as CSM for the corporation. Moreover, in 2019 Chuquicamata Underground Mine will be commissioned, a block caving operation that required over US$ 5.5 billion for its construction and will extend the life of Chuquicamata Division for at least 40 years[11].

4.2 General description of the project

The concept of continuous mining for caving operations was first introduced by Codelco and its Institute for Innovation in Mining and Metallurgy, IM2, in 1998. It was conceived as a tool to face the future challenges of underground mining, specifically the necessity of increasing extraction rates and improving safety (Carrasco, Encina, & Le-Féaux, 2004).

This mining design was based on the following key elements (Carrasco et al., 2004; Orellana, 2012):

- Application of preconditioning to ensure a proper fragmentation of the rock mass and an uneventful flow of broken ore through drawpoints.
- Continuous and simultaneous extraction from active drawpoints by dozer feeders, increasing extraction rate and utilisation.
- Continuous transport of material by panzers.
- Early size reduction of ore by sizer crushers.
- Remoted operation of the system, reducing workers exposition and increasing productivity.

A simplified scheme of the CMS design is presented in Figure 24, showing the location of the main equipment considered for this method: dozer feeders at the drawpoints, panzers to collect and transport the broken ore from the dozers to the sizer crushers, and finally the sizers themselves.

Changing the operation of LHDs for a continuous material handling system also requires a reorganisation of the layout of the extraction level. The differences between the El Teniente layout (typically used by Codelco in its caving operations) and the CMS layout are presented in Figure 25.

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[11] Information available in https://www.codelco.com/

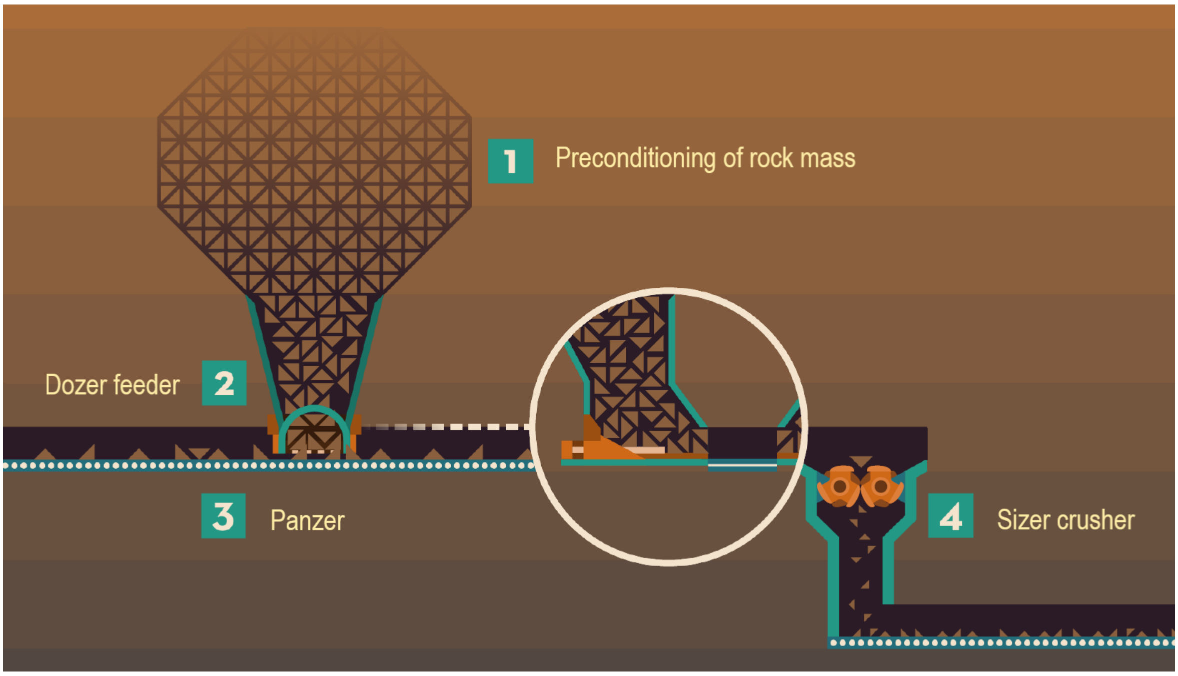

Figure 24: General scheme of CMS design.
Taken from Baraqui (2014).

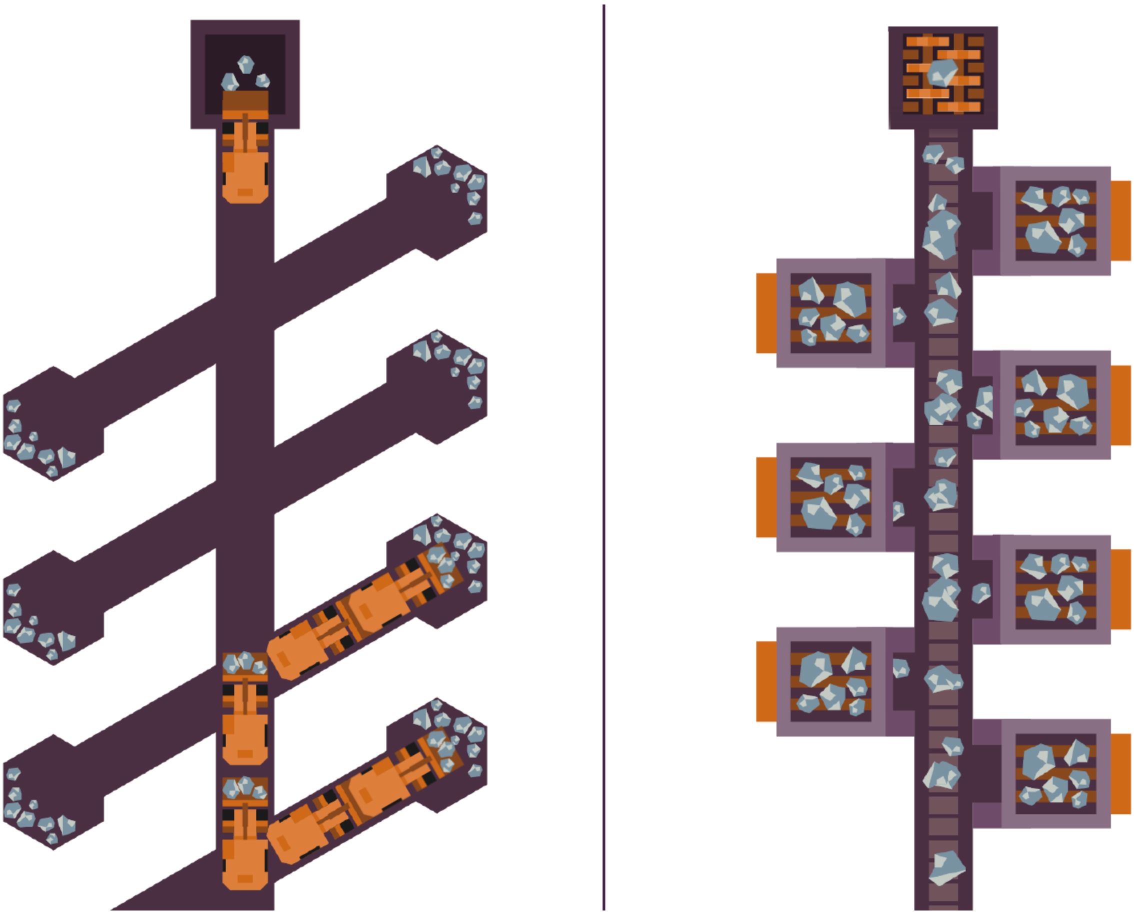

Figure 25: El Teniente layout (left) vs. CMS layout (right).
Taken from Baraqui (2014).

4.3 Process validation of CMS

After years of research since the concept was first introduced in 1998, the process validation for the CMS design was carried out in three phases, as shown below.

4.3.1 Phase I: Dozer feeder

The first phase took place in Codelco's Salvador Mine, in 2005. It was focused on the validation at a pilot level of the concept of continuous extraction (Figure 26). For this, the extraction of ore from one drawpoint by a prototype of a dozer feeder was tested (Figure 27).

The test showed the capacity of the dozer feeder to extract the ore from the drawpoint at a reasonable rate (200 tonnes per hour in average), allowing a proper flow within the ore column (Orellana et al., 2017). With these positive results, the process validation moved forward to Phase II.

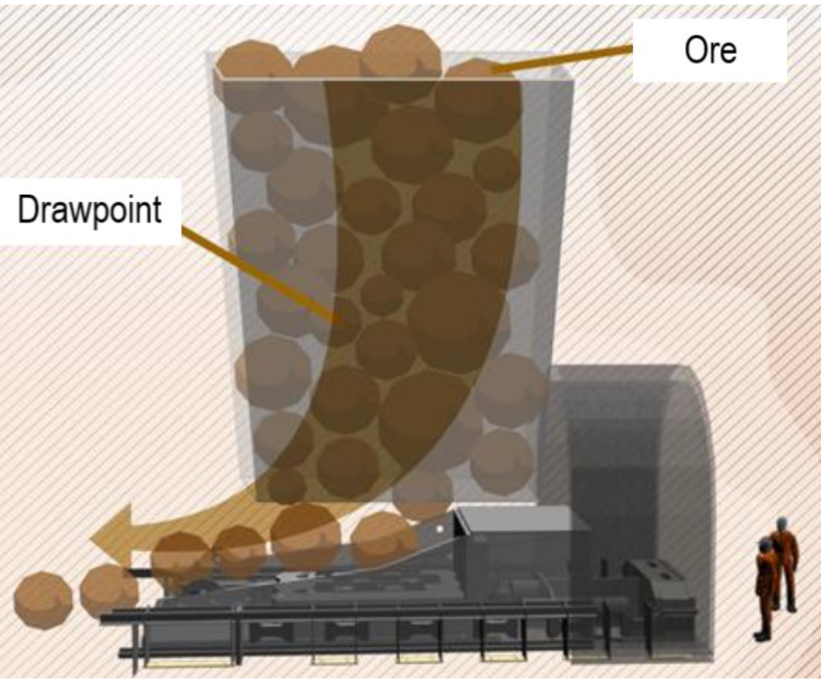

Figure 26: Scheme of continuous extraction from drawpoint by a dozer feeder. Taken from Baraqui (2014).

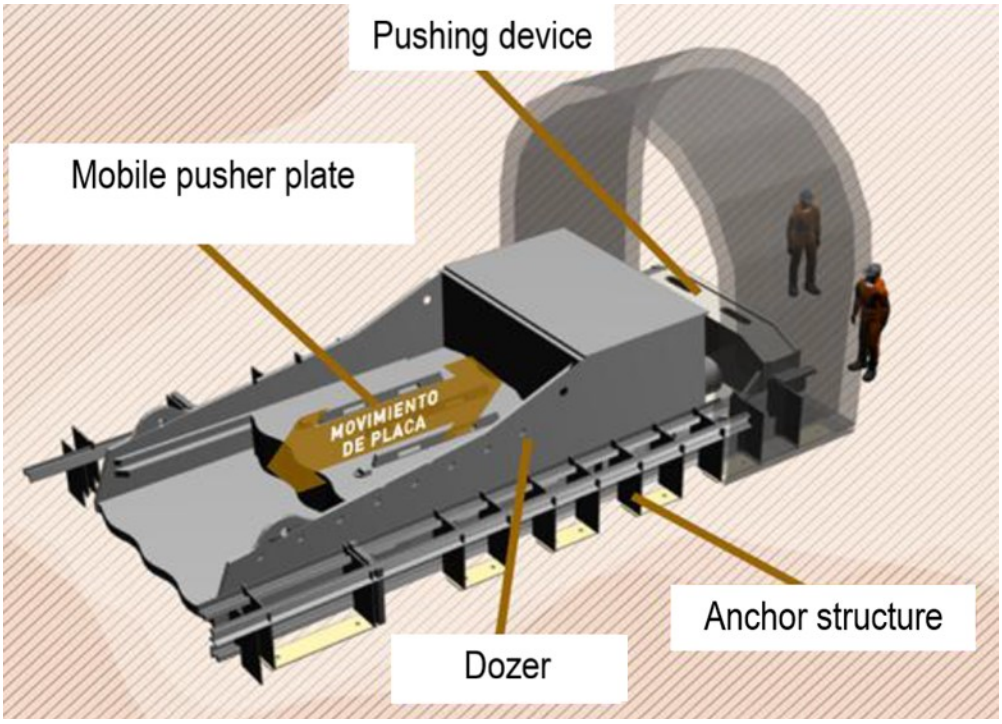

Figure 27: Scheme of dozer feeder tested during Phase I.
Taken from Baraqui (2014).

4.3.2 Phase II: Module CMS

The second phase in the process validation of CMS was also executed in Salvador Mine. This time, a prototype of a modular system of continuous extraction, haulage and crushing was tested (Figure 28). The module considered one haulage drift with four drawpoints, each one of them with a dozer feeding the panzer, which transported the ore to a roller impact crusher (Baraqui, 2014). The module was built between 2006 and 2007 and the test itself carried out between 2007 and 2008. During this period, approximately 200,000 tonnes were extracted in total. The results achieved in Phase II were satisfactory, in terms of the performance of the different equipment and their interaction, though the roller impact crusher was dismissed for further tests due to its low availability and high components wear. In its place, sizer crusher was incorporated afterwards (Orellana, 2012).

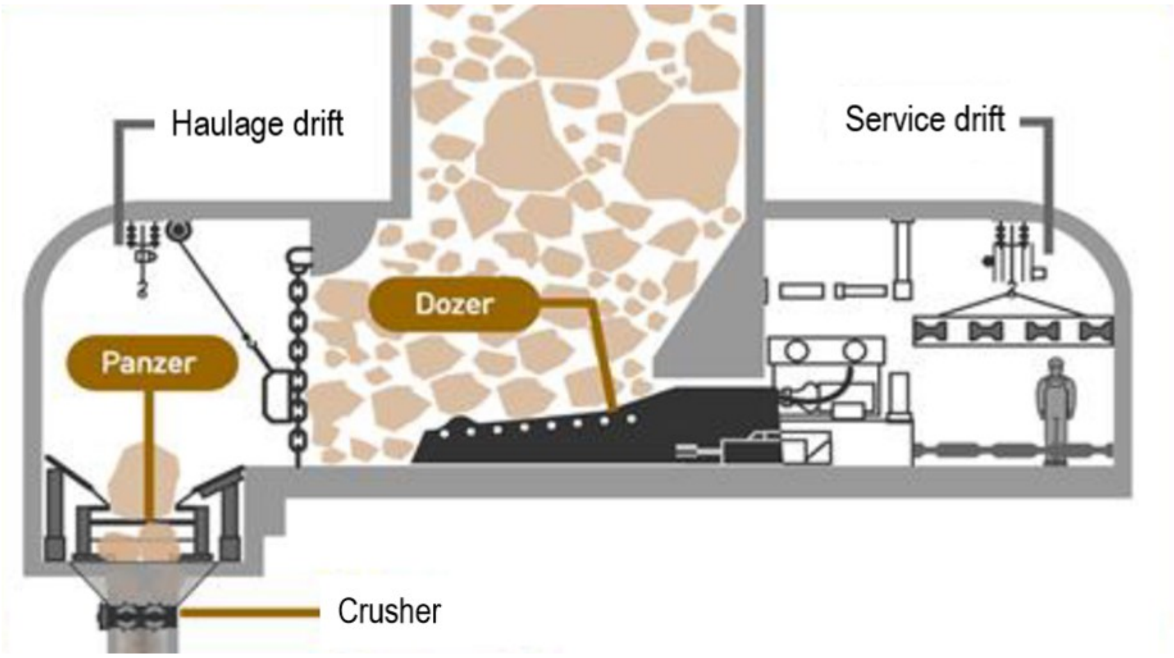

Figure 28: Cross-section of extraction level in modular CMS, Phase II.
Taken from Baraqui (2014).

4.3.3 Phase III: Industrial validation of CMS

Due to the promising results in previous phases of validation, the company decided to move forward to Phase III, to validate at an industrial level the CMS method. This test aimed to evaluate the performance of the CMS method under real operating conditions, in Andina Division of Codelco. The design considered a sector of four haulage drifts (equipped with panzers) and eight drawpoints per drift (each one of them equipped with a dozer feeder), and a total test period of 38 months (Figure 29) (Baraqui, 2014).

Phase III was defined as the validation test of CMS for its application in the Chuquicamata Underground Mine Project, which commissioning is planned for the first semester of 2019. In this sense, the main expected benefits from its applicability in the Chuquicamata Underground Mine originally were (Baraqui, 2014):

- Instant production rate: 3 t/m^2-day.
- OPEX: 20% lower.
- Workforce requirements: 30% lower.

- Ramp-up period: 25% shorter.
- Improvements in safety and energy efficiency.
- Net present value for its application in Chuquicamata: US$ 1,000 million.

Figure 29: Design of test module for CMS, Phase III.
Taken from Baraqui (2014).

The construction of the test module started in 2012. However, due to significant deviations in the execution period and budget, the works were stopped in December 2015. After more than two years of being paralysed, and in the light of new studies and re-evaluations performed by Codelco, the project was finally cancelled in 2018, totalising US$ 138.1 million of loss (Codelco, 2018b).

4.4 Analysis and discussion

From Codelco's experience in the process validation of the CMS innovation project, several key elements can be identified, and lessons can be learned:

- **Time required for process validation:** Developing an innovation project for a technological breakthrough often requires long periods of time. Since the idea is conceived, conceptual studies must be carried out before initiating pilot and industrial validation tests. In the case of Codelco's CMS, over twenty years passed since the concept was first introduced until the industrial validation project was finally cancelled. During this time, other technologies are developed, that can be incorporated in the innovation project being tested, changing its potential value and future impact of its application. Specifically, during the process validation of CMS significant advances were made in preconditioning techniques and digital technologies (e.g. automation, robotics). The project team must evaluate the impacts of new technologies developed along the way and incorporate them in the project if they prove to add value.

- **CAPEX and execution period estimation:** Process validation can be expensive, especially industrial validation phase. Special care must be taken in the economic evaluation that justified the project and in the execution time and budget estimation. CMS project was stopped and finally cancelled due to problems in its construction phase, not because of unsatisfactory results of the test itself: this didn’t even get to be executed.
- **Infrastructure required and coordination with the operation:** New designs for extraction and material handling methods must be proved under real conditions for their industrial validation. For this, first the company needs to have access to ongoing mining operations, of its own property or coordinate with another company, in other case. Then, a proper coordination with the current operation must be conducted, to minimise interferences and ensure the availability of resources (e.g. energy, water).

It is important to highlight the relevance of the CMS project, regarding its potential to improve extraction rates and safety in caving operations. Material handling systems through batch operations, such as the use of trucks and LHDs, are highly inefficient, from a macro point of view. Equipment show low levels of utilisation and the productivity of the overall operation remains restricted. The design proposed by the CMS initiative offered the possibility of achieving higher production levels with lower requirements of active area, reducing CAPEX and OPEX, and gaining future dividends of the project earlier in time. All these factors have a positive effect in the economic indicators of a mining project: net present value increases and payback period is reduced, for example .

Finally, continuous mining and automated operations are trends that will likely shape the mining of the future. Initiatives like the CMS design should not be immediately dismissed, especially considering that this particular project failed in the construction stage of its industrial validation phase, having no chance to prove its applicability (or inapplicability) in a real operation.

5 Conclusions

Innovation plays an important role in the mining industry as a tool to improve the efficiency of its processes, reduce costs, but also to meet the increasing social and environmental concerns among communities and authorities. Technological progress has also been crucial to allow the exploitation of new deposits in more complex scenarios: lower ore grades, extreme weather conditions, deeper deposits, harder rock mass and high-stress environments.

In concrete, the importance of innovation for the mining industry, as a critical factor in the improvement of labour productivity through past decades, was analysed. Though its relevance, mining companies usually show low levels of R&D intensity, similar to mature industries and far from high-tech sectors. The tendency to vertical disintegration has led firms to focus on their core business, relying mainly on equipment manufacturers and suppliers for the development of innovative solutions. Also, collaborative alliances between mining companies, suppliers and research centres share a significant participation in the development of new technologies.

Nowadays, several technological trends can be identified as main factors that will shape the mining of the future. The first and most relevant one is the digital transformation (DT), as the process of adoption and incorporation of a set of tools, the so-called technologies 4.0, into the mining business. Automation, robotics, remotisation of operations, internet of things, analytics, digital twinning, among others, have the potential to enhance processes along the whole value chain of mining. However, though DT is frequently mentioned as one of the main concerns among most of large-scale mining companies, the level of digitisation of the industry remains low, indicating that most of the potential of DT for the sector is still to be unlocked. The main challenges that firms must face to achieve a successful digitisation are the commitment and joint-task coordination between the different business units, implementing proper organisational structure changes, and promoting a new cultural mindset regarding cybersecurity strategies and their continuous improvement.

Other important trends are electromobility, invisible zero-waste mining and continuous mining. These concepts answer to the necessity of building a more sustainable and efficient industry, reducing the environmental footprint and enhancing safety of mining operations. On one side, the replacement of fossil fuel-powered vehicles is a “must” in a world moving away from such energy sources to cleaner ones, and stricter safety and environmental regulations being implemented all around the world are a reflect of that. Nowadays, more companies are evaluating the incorporation of electric-powered fleet into their operations, as existing technologies can already offer economic alternatives, while R&D keep advancing in this matter.

Invisible mining strategies, such as in situ leaching methods, have minimal impact on the surface and surroundings, and generate practically no waste. Yet, for a widespread application of this mining method progress must be made in rock mass permeability enhancement (e.g. preconditioning techniques) and hydrogeological management, to ensure an optimal leaching process, in the first case, and minimise risks associated to groundwater pollution, in the second one.

Finally, though the concept of continuous mining has been applied for many years in the coal mining industry, its application in other mineral sectors has the potential to increase productivity, reduce costs and improve safety, along with technological tools brought by DT, such as automation, robotics and remotisation of operations.

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8 List of Abbreviations

BBS	Bottom blowing smelter
BCC	Bottom blowing continuous converting
CAPEX	Capital expenditure
CB	Confined blasting
DT	Digital transformation
HF	Hydraulic fracturing
ICE	Internal combustion engine
ICT	Information and communications technology
IoT	Internet of things
ISL	In situ leaching
ISR	In situ recovery
IT	Information technology
LHD	Load, haul, dump machine
METS	Mining equipment, technology and services
OECD	Organisation for Economic Co-operation and Development
OPEX	Operational expenditure
OT	Operational technology
PTD	Paste tailings disposal
R&D	Research and development
ROC	Remote operation centre
SX-EW	Solver extraction and electrowinning
TSF	Tailings storage facility
TTD	Thickened tailings disposal