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Innovation and Competitiveness in Mining Value Chains

The Case of Brazil

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ABSTRACT

Mining companies have mirrored other large multinational companies in setting up global value chains (GVCs), sourcing their inputs and services from an ever-larger number of highly capable suppliers in developing countries, such as those in resource-rich Latin America. However, recent empirical studies on the mining GVC in that region suggest that even innovative local suppliers find it difficult to exploit their innovations in local and foreign markets. Using a conceptual framework that combines literature on innovation and GVCs, this study analyzed how global/regional-and firm-level factors interact to explain the acquisition of local suppliers' capabilities within Brazil's mining industry. The study explored these issues using original data gathered in 2019 and secondary sources from Brazil. The main findings are related to

- strategies used by domestic suppliers to develop innovative solutions for leading mining companies,
- how health and safety concerns spurred innovation after the disasters in Mariana and Brumadinho,
- new-to-the-world innovation capabilities among Brazilian suppliers to the mining industry, and
- the main barriers to developing innovative practices among domestic suppliers.

The authors propose public policies to support major mining companies in acquiring innovations from domestic suppliers to the mining industry. Opportunities such as a Copper Rush in Brazil that could foster further innovations in mining are discussed.

JEL Codes: O13, O31, Q56, L72, M11

Keywords: Innovation, Technology, Innovation Incentives, Innovation Management, Innovation Processes, Innovation Firm, Technological Innovation, Suppliers, Metals, Value Chains, Government policies, Public policies, Environmental impact, Sustainability, Commodities, Mines, Mining, Extractive, Natural Resources, Copper

1. INTRODUCTION

Brazil has a strong tradition of producing and exporting commodities and is one of the main global suppliers of mineral products. Mining of metals and non-metallic minerals take place all over Brazil's vast territory. Iron ore is by far the main metallic product for which the country is known, accounting for over 70 percent of commercial production, followed by copper with 9 percent. However, recent discoveries and large known deposits of copper suggest its potential is yet to be realized (ANM, 2020a).

The sophistication and variety of local and international suppliers and service providers to the copper sector and to the mining industry in Brazil as a whole is staggering. This variety has developed thanks to Brazil's mining sector being spread across its territory, providing opportunities for mining equipment, technology, and services that can work in tropical, Indigenous, and remote environments as well as in the desert, urban areas, and mountainous regions. However, after the economic crisis of 2014–18, many domestic firms disappeared or were absorbed by multinationals, so there is a lack of information about the surviving mining sector suppliers and whether they are capable of becoming innovative partners with mining companies and thrive.

This study contributes to understanding the main opportunities and challenges to developing a critical mass of local innovative suppliers for copper production in Brazil to support diversification, innovation, and growth. In particular, the aim is to understand whether and how the current organization of the country's copper mining value chain is creating opportunities for local suppliers to innovate and if public policies could support this process.

To explore the proposed research questions, the copper value chain in Brazil was mapped to identify the links where domestic suppliers operate.

The study focuses on the mining stages: exploration, mine construction, and operation. Given the goal of finding innovative practices, local strategic mining suppliers were selected for this study through in-depth field research. Therefore, there is a purposeful bias toward innovative firms. The

study explores the challenges local suppliers have faced when entering the mining value chain and which strategies have been successful in overcoming those challenges. Another key area of research was how suppliers acquired the capabilities and resources that allowed them to maintain their positions as innovative suppliers to their clients.

The study also looked at the institutional context for mining in Brazil. Desk research and interviews with mining companies, mining suppliers, government institutions, and other key stakeholders in the sector were key to understanding the institutional framework of mining in the country, the institutions that affect the sector and their roles, and the laws and regulations that play a role in fostering or hindering sustainable growth of copper mining in the country.

The document is organized as follows. The next section briefly discusses the conceptual framework, defines the objectives, and presents a summary of the methodology. The following section provides an overview of mining activity in Brazil, particularly copper. Then we analyze the main evidence regarding Brazilian firms' development of suppliers and the supply chain that was collected during fieldwork. The final secion highlights the main findings and provides policy recommendations.

2. CONCEPTUAL FRAMEWORK, OBJECTIVES, AND METHODOLOGY

In contrast with the pessimistic view that natural resources are a curse for economic development, recent studies of innovation argue that substantial changes in international institutions, markets, and technologies over the past few decades have created a new and more diverse set of opportunities for a larger number of developing countries to develop dynamic and innovative industries based on natural resource endowments (Marin, Perez, and Navas-Aleman, 2015; Pérez, 2010). Thus, the literature poses a challenge for researchers trying to understand these new opportunities. The argument is that, although it is important to understand the path followed by countries that have managed to succeed in using natural resources for economic development (e.g., Canada, Australia, and the United States), it is also crucial to understand which new opportunities and challenges countries rich in natural resources are facing in the current context to provide informed inputs for public policy.

The mining sector provides an excellent opportunity for research because it experiments and because it is undergoing important changes that can create opportunities for diversification, innovation, and growth. Since the 1970s, there has been a major transformation in mining activity, with the industry exhibiting (Bloch and Owusu, 2012; Figuereido and Piana, 2016; Molina, 2017; Morris, Kaplinsky, and Kaplan, 2012; Stubrin, 2017; Urzúa, 2011):

- a combination of growth, international relocation, and innovation;
- a process of technological rejuvenation in which a large number of technological innovations and improvements in exploration, mining, and mineral processing have been driving industry development;
- a change in the organization of production toward vertical disintegration and internationalization of large mining companies;
- and the emergence of specialized and knowledge intensive suppliers in many developed and developing countries.

Mining companies have mirrored other large multinational companies in developing global value chains (GVCs), sourcing their inputs and services from an ever wider number of countries, thus creating opportunities and challenges for suppliers in developing countries, such as those in Latin America.

This study explores opportunities and challenges related to developing the mining sector in a way that furthers innovation by domestic suppliers and strengthens their integration in copper mining value chains in Brazil. The objectives of this study include:

- Understanding and **mapping** the copper value chain in Brazil, identifying actors, activities, and institutions involved in the chain, as well as their main features and characteristics.
- Identifying the **stages or activities** of Brazil's copper value chain where domestic suppliers operate (excluding simple commodities like energy, transport, and food).
- Identifying **innovations** among suppliers and the key factors that hinder or facilitate them.
- Exploring **opportunities and barriers** for local suppliers to approach lead firms in mining value chains to develop innovations.
- Exploring how **governance** (linkages within the value chain) limits or increases suppliers' chances of developing innovative solutions and then exploiting them.
- Identifying potential **public policies** to support the innovation capabilities of suppliers.

To address these objectives, our theoretical framework combines insights from literature in two areas: innovation and GVCs. The innovation literature is vast, but the present study draws on a combination of the capabilities approach (Bell and Pavitt, 1992, 1995; Figueiredo, 2006; Lall, 1992, 2001) and the resource-based view (Penrose, 1959; Prahalad and Hamel, 1990; Teece, Pisano, and Shuen, 1997) to capture the internal factors that affect a firm's acquisition of innovative capabilities.

The **capabilities approach** uses descriptions and comparisons to identify different levels of attainment (from basic to advanced) of innovative capabilities within firms. An important tool is recalling innovations or a firm's major decisions to collect data about the previous knowledge and efforts that allowed firms to acquire new capabilities. In its original form, this approach focuses on technological innovations.

The **resource-based** view proposes that each firm owns and controls a unique bundle of tangible and intangible strategic resources (including capabilities) that enables them to be more competitive (Barney, 1991; Penrose, 1959). Apart from its tacit nature (Polanyi, 1962, 1966) and its embeddedness in relationships and people, intangible knowledge has a third dimension that makes it difficult for competitors to copy and is therefore part of a firm's resources: it is path dependent. Path dependency (David, 1986; Teece, 1988) essentially argues that what a firm can do tomorrow is largely based on what it can do today. A developing country supplier to the copper value chain that faces barriers to expand and acquire capabilities in higher value added activities can remain trapped in its current main activity because of path dependency and see other firms surpass or control them.

The GVC literature also explores technological learning and upgrading within firms, but emphasizes the role of power relationships and issues of governance in explaining different rates of success for small firms' learning (Gereffi, 1994, 1999). By exercising power, lead firms in GVCs (including domestic firms) have a major influence on the distribution of capabilities and gains among the participating firms (Kaplinsky and Morris, 2001). There are different types of chain governance based on different levels of control over strategic capabilities and different levels of dependence

between the supplying firms and the lead firm (Gereffi, Humphrey, and Sturgeon, 2005; Humphrey and Schmitz, 2004):

- Hierarchy (buyer owns the supplier; e.g., MNC-subsidiary trade)
- Captive networks (one firm sets all parameters and controls the other firms in the chain)
- Modular networks (firms are close collaborators, their strategic capabilities are complementary, and no firm exerts undue control over the other)
- Arm's length market relations (no need for close collaborations as the product is standard and available from many sources)

Regarding innovative capabilities that could make input suppliers and service providers upgrade and potentially compete with lead firms, the GVC literature has found that captive networks are (i) the least conducive for their acquisition and (ii) the type of chain governance to which developing country producers are most commonly exposed when joining GVCs (Schmitz, 2004; Giulianni, Pietrobelli, and Rabellotti, 2005, Navas-Aleman, 2011).

In the mining industry, power issues seem crucially important since large firms tend to dominate the value chain and there is an important power asymmetry between large mining firms from developed countries and local suppliers in developing countries.

Our integration of the innovation and GVC literature provided us a comprehensive view of how factors operating at the global/regional and firm levels interact to explain the acquisition of capabilities by local suppliers.

Based on this integration, we considered three types of capabilities that are important for local suppliers to innovate in the mining industry:

1. Technology
   - New to the firm, new to the country, and new to the world
   - Product, process, marketing, and organization
2. Negotiation/collaboration with other firms (within the value chain governance)
3. Negotiation/collaboration with universities, research centers, and other entities

This combined conceptual framework allowed us to explore factors highlighted by recent empirical studies on the mining value chains in Peru, Chile, and Brazil, whereby issues of governance were shown to affect local suppliers' opportunities for growth and to participate in the value chain (Molina, 2018; Pietrobelli, Marin, and Olivari, 2018; Stubrin, 2017). These studies showed that a number of domestic firms in these three countries were able to benefit from opportunities provided by new technologies like IT or biotechnology. However, innovation opportunities were constrained by the small amount of support provided to local suppliers by leading mining companies in the process of developing the innovation (Molina, 2018; Stubrin, 2017). The hierarchical governance of those value chains did not favor quality linkages between lead firms and suppliers, reducing suppliers' learning and innovation potential. The evidence also showed that local suppliers tend to have high technological capabilities but find more difficulties building non-technological capabilities (e.g., negotiating with large mining firms, finding experimental spaces to test their innovations, and developing an effective commercial strategy) to exploit their innovations in the local and foreign markets (Marin, Dantas, and Obaya, 2016).

This study explored these issues using original data and secondary sources from Brazil.

3. METHODOLOGY

Although the focus of the study was the copper value chain, and more precisely, the domestic suppliers serving this value chain, it became clear that most suppliers do not segregate their activities according to the minerals their clients produce. In most cases, suppliers' services or products can work with different minerals and mining firms, making it extremely difficult to isolate the copper value chain from other mineral value chains. Therefore, despite keeping the copper value chain as the main subject of this study, many of the supply firms that we interviewed also operate in different chains within the mineral industry. As a result, some of the findings are likely to reflect wider practices in the mining industry and are likely to be generally applicable beyond the copper value chain.[1]

Moreover, while it was possible to analyze innovation at different stages of the mining cycle and in different sectors, it proved to be less practical to analyze innovation according to firm size and tier. We were unable to compare the size of our sample with the entire population as there are no reliable or complete lists of suppliers to the mining value chains. A full explanation of the official databases that were consulted and the challenges faced in our attempts to build a list of mining suppliers (using PIA Produto, PIA Empresa, and Pintec Technology Holdings Ltd. [PINTEC] and a recent attempt by the Brazilian Industrial Development Association [ABDI] to create a supplier database) is presented in the appendices.

Mapping the institutional and regulatory context for mining in Brazil was achieved by interviewing regulatory bodies, business associations, and state-level agencies responsible for policy-making in mining.

Fieldwork was developed in two phases:

1. An **exploratory phase** to familiarize ourselves with the institutional and business landscape for mining and to gather important sources of data. During this phase, we carried out 25 in-

1 The parallel value chain research done in Argentina experienced similar issues; hence, together, the studies provide more general insights on the mining industry.

terviews (three major mining firms, three mining suppliers, and 19 government and technical institutions) between February and May 2019.

2. A **survey phase**, which consisted of **28 interviews** (suppliers and service providers, three of which were interviewed in the exploratory phase). Evidence was gathered using differentiated research instruments for firms, institutions, and suppliers. Interviews started in late July, with 26 carried out in Minas Gerais, two in Para, and one in Rio Grande do Sul. The research instruments are provided in the appendices. Note that none of the suppliers selected were start-ups; however, during the exploratory phase, the Mining Hub in Belo Horizonte provided us the opportunity to have conversations with a number of start-ups.

Complementary information was gathered by attending specialized events in Brazil (e.g., EXPOSIBRAM), reviewing sector reports and documents, and visiting copper mines (Chapada in Goiás and Salobo in Pará).

The criteria to identify local strategic mining suppliers was to single out domestic firms that provided specialized goods and/or services strategic for the mining value chain in terms of their monetary value, their discretionary power, and their unique knowledge and productive capabilities. For example, suppliers that provide monetary value are those whose products or services represent a significant share of mining costs (e.g., heavy machinery). Suppliers with discretionary power include, for example, labs that provide tests and certifications. And suppliers that are strategic in terms of their unique knowledge and productive capabilities develop specialized goods and services for mining construction and operation. Therefore, we deliberately excluded companies that supply generic products or services, such as general transport or catering.

The selection process had three stages:

1. We gathered as many reliable lists of suppliers as possible in the exploratory phase. Brazil does not have an official register of mining suppliers and the national statistics classifications tend to include copper suppliers with all suppliers to non-ferrous metals value chains. Besides, suppliers to the iron industry often work with firms that mine copper and other minerals.[2]
2. We identified companies that other firms and institutions mentioned as innovative or strategic.
3. We used snowball sampling by getting interviewees to refer us to other firms suitable for the study. This a classic value chain referral sampling technique that is proven to help build a sample when there is no comprehensive list of the value chain population. Appendix 1 provides a full explanation of the different stages of the sampling process.

Two factors made fieldwork for this project particularly challenging. First, as 2019 progressed, the fallout from the Brumadinho disaster made mining companies (and their suppliers) more reluctant to be interviewed. Second, an unforeseen crisis in the airline market increased airfare beyond the original budget, which forced us to rethink the sample size and the number of team members involved in fieldwork. However, despite these difficulties, the research objectives were achieved and

2 This lack of a clear list caused extensive problems for our methodology. We provide more about how we overcame these issues in the appendices.

the quality of the data collected remained high. If the research had been deterred by these circumstances and been postponed to 2020, it would have encountered a much worse crisis: Covid-19.

Instrument to Survey Suppliers

We used a semi-structured questionnaire structured as follows:

- **Firm characteristics**: ownership, history, date of foundation, activity, main products and services, and competitive advantage.
- **Type, origin, and characteristics of main clients and suppliers**: number, name, and type of main clients; sector of origin of clients; main clients' proportion in total market sales; main suppliers; main inputs firms acquire from them; and participation of foreign/local capital in the chain.
- **Participation in the mining value chain**: the main links in the chain that the firm provides inputs and services to.
- **Size of firm and other quantitative indicators**: sales, number of employees, exports, and profits (2018 and 2013–2018).
- **Technological capabilities**: qualifications of human resources, innovation efforts and results, sources of information and knowledge needed to innovate, main technological areas, role of regulations in innovation activities, and intellectual property rights.
- **Non-technological capabilities**: structure of firm, decision processes, and main barriers faced when introducing an innovation to the market.
- **Governance**: types and characteristics of linkages with clients, local governmental agencies, financial institutions, chambers of commerce, and knowledge institutions.

The interviews were carried out over a six-week period starting July 29, 2019, followed by a 10-day period for telephone interviews starting September 16, 2019. On average, each interview lasted 1 hour and 54 minutes. Appendix 7 provides the list of firms cited in the exploratory interviews as important and innovators. The list of websites we used to increase our sample is provided in the references.

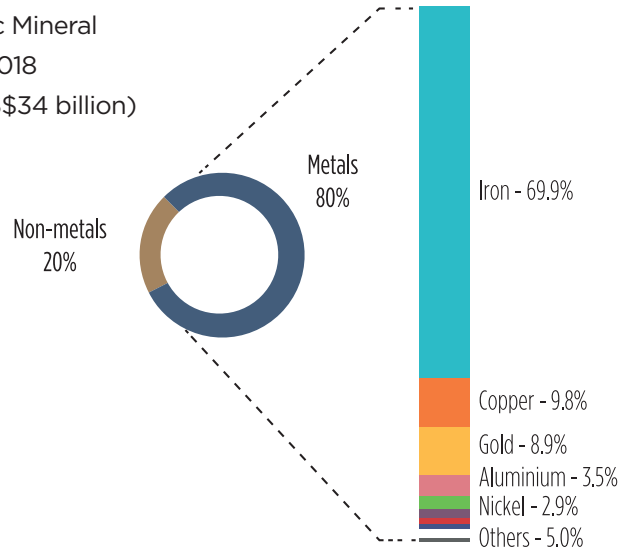
4. THE BRAZILIAN COPPER MINING VALUE CHAIN

Overview

Brazil is a country with a strong tradition of producing and exporting commodities and is one of the main global competitors in mineral products. Brazil is the largest exporter of niobium, the second largest exporter of iron ore, and the third largest exporter of vermiculite and graphite. Bauxite, tin, nickel, gold, manganese, and copper (to mention just a few) are also on the list of mineral substances exported by the country (IBRAM, 2020a).

Figure 1 shows the distribution of Brazil's metallic mineral production in 2018. Iron ore is by far the main metallic mineral product in Brazil, accounting for almost 70 percent of commercial production, followed by copper at almost 10 percent.

Figure 1. Distribution of Metallic Mineral Production in Brazil, 2018 (% of total value of US$34 billion)



Source: ANM (2020b) and IBRAM (2019a).

To provide some context for the strategic importance of the mining sector in Brazil, in 2018, the extractive sector, which includes mining, accounted for approximately 4 percent of Brazil's overall GDP and 17 percent of industrial GDP. The mining industry's contribution to GDP was 1.4 percent, with mining accounting for 34 percent of Brazil's trade balance.

In Brazil, 165,000 workers are employed in the mining sector and its support activities, but it is estimated that the sector generates about 2 million jobs directly and indirectly. In 2018, revenue from mining was roughly US$34 billion, of which almost US$30 billion was exports. Iron ore represented 68 percent of that year's exports, followed by gold (9 percent) and copper (9 percent) (IBRAM, 2019a). The variety of substances is another indicator of the country's mineral wealth. In total, the National Mining Agency (ANM) has registered licenses to explore or mine 37 different metal substances, 11 of which account for 80 percent of commercialized production and are therefore considered the main metallic minerals (ANM, 2020b). Most metallic production is concentrated in two states—Pará and Minas Gerais—which together account for 89 percent of the mining production value. However, there are clearly identified mineral reserves in 13 Brazilian states (50 percent of all states) (ANM, 2020b). Figure 2 shows the mining reserves throughout Brazil.

In 2019, Brazil had 9,415 active mines. Of these, 207 were extracting the main metallic minerals shown in Figure 1. In 2018, the mining authorities granted over 3,000 mining licenses (Table 1), most of which (93 percent) were for mineral exploration.

Table 1. Authorizations Granted in 2018 for Research and Exploration (Metallic Minerals)

Type of Authorization	No.	Region*
Mineral exploration	3,310	Middle-west (30.7%)
Mining license	53	Middle-west (40.9%)
Open pit digging permit	173	North (72.9%)

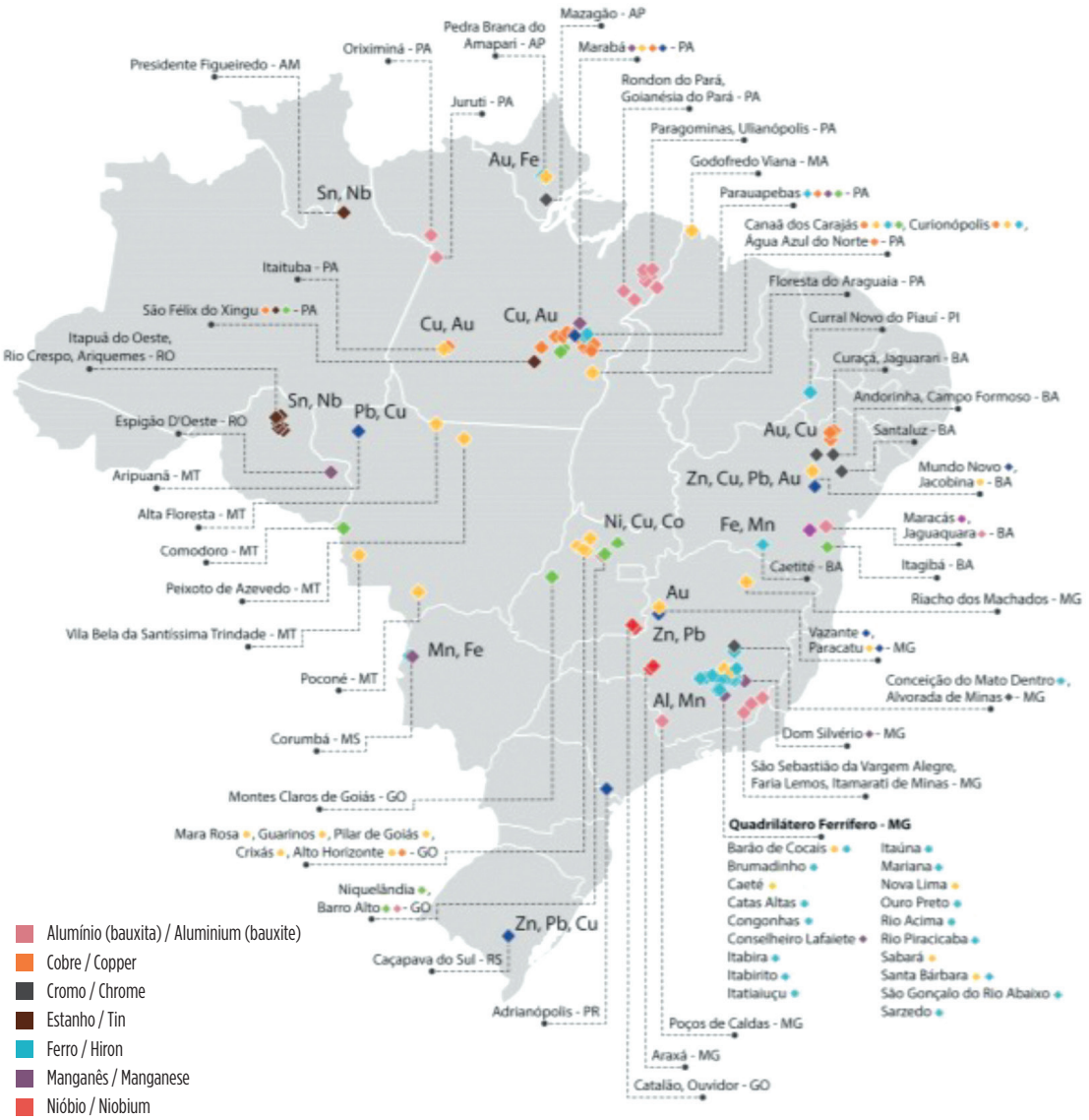
Source: ANM (2019).
* Metallic mineral mining as a percentage of total mineral mining (including non-metals).

Only 2 percent of the mines can be classified as large, which is defined by run-of-mine production above 1 million tonnes per year. Similarly, of the existing 95 mineral processing plants, the majority are small and medium sized (below 1 million tonnes per year). Metallic mineral mines (different from those for construction materials) tend to be significantly larger and 33 percent of those are classified as large (ANM, 2020b; IBRAM, 2019a).

Despite being a major exporter of minerals, Brazil also imports many mineral products. The primary goods trade balance is positive, reaching over US$21 billion in 2018 (IBRAM, 2019b) or US$35 billion including primary plus semi-manufactured and manufactured goods (ANM, 2018).[3] The mineral trade balance grew 33.2 percent compared to 2016, reaching US$24 million in 2019 (IBRAM,

3 While IBRAM considers mining production of all minerals (metal and non-metal), the ANM only considers metallic minerals and includes products from other stages of the value chain, such as semi-manufactured and manufactured products.

Figure 2. Main Identified Mining Reserves (Al, Au, Cr, Cu, Fe, Mn, Nb, Ni, Sn, Zn), 2018



Source: ANM (2020b).

2018, 2019b). In monetary terms, in 2019, the main imported minerals were carbon (non-metallic; 32 percent) and potassium (42 percent). Copper accounts for 6 percent of imported minerals (IBRAM, 2018, 2020a).[4]

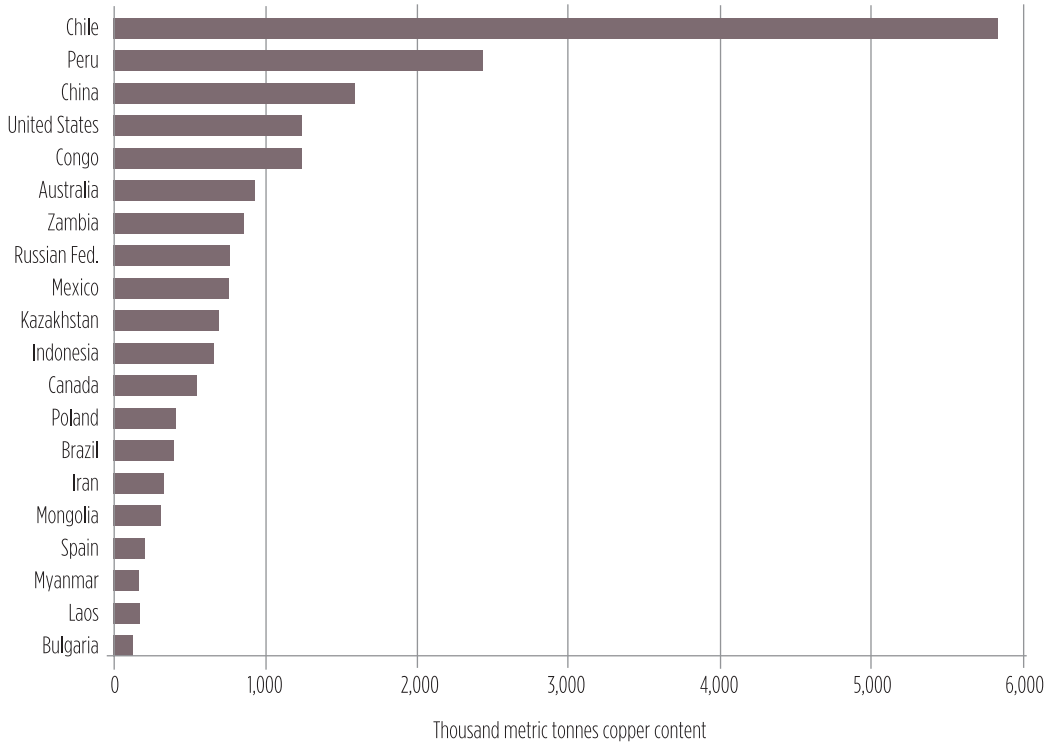
4 Considering only metallic minerals, copper ranks second (21.0 percent) after iron (50.5 percent), followed by aluminum (18.9 percent) (ANM, 2020a).

A more detailed look at the trade balance in metallic minerals shows that there is still a lot of potential for Brazilian companies to add value in the production chain. While 50.8 percent of exports correspond to minerals in their primary form, 88.3 percent of imports are semi-manufactured or manufactured goods (ANM, 2020b).[5]

Copper Reserves, Production, and Commercialization in Brazil and Around the World

Global production of copper concentrates reached 20.6 million metric tonnes (Mt)[6] in 2018 (ICSG, 2019). Chile ranks first among producing countries with production of 5.8 million Mt, followed by Peru at 2.4 million Mt and China at 1.6 million Mt. Though Brazil is still far from being considered a major competitor with production of approximately 386,000 Mt in 2018 (ANM, 2020b), its contribution to the copper market is significant. The country is ranked fourteenth among global producers (Figure 3) and accounts for 1.9 percent of the production market.

Figure 3. Top 20 Copper Producing Countries, 2018



Source: ICSG (2019).

5 Foreign trade data is subdivided into primary goods, semi-manufactured goods, manufactured goods, and chemical compounds. This classification denotes increasing added value. Products follow theHarmonized Tariff Schedule of Mercorsur, which is based on the Harmonized Commodity Description and Coding System.

6 Mt = Metric tons. Note some graphics and tables will use t and Mt interchangeably.

Brazil's current copper reserves are assessed at 11.2 tonnes, or 1.6 percent of world reserves (SGM, 2020), and exploration activity will probably increase that number. For instance, in 2017, the map of Brazil's identified reserves published by the ANM (Figure 2) was modified to reflect increases in two states compared to the previous year (ANM, 2020a; DNPM, 2017a). According to key informants in the sector, a mere 5 percent of the national territory has been properly mapped, which means that the likelihood of new discoveries and investments is high for copper and other minerals.

Moreover, the copper in Brazil's reserves have been assessed to be of good grade, which is likely to attract investments. The ANM reports that in 2018 the average grade of copper production was 0.72 percent, a significant increase from 0.55 percent in the previous year. While it is not an outstanding result,[7] in some regions, such as Bahia, tests have revealed the grade may reach almost twice this figure (up to 1.31 percent). Moreover, recent tests in Pará have discovered a reserve with grades varying from 1.93 percent to 3.98 percent (Vaz, 2018). In many cases, those results put Brazilian grades above those in Chile and Peru. In a scenario with depleted reserves all over the world, Brazil has the potential to become a much larger producer.[8]

The potential for new discoveries combined with the quality of the reserves place the country in a strong competitive position, since the higher grades are mostly available at open-pit mines, thereby reducing production costs, increasing profitability, and attracting larger investments.

The main identified copper reserves are located in Pará (which has the biggest Brazilian mineral reserves, the Serra dos Carajás), Goiás, and Bahia, the three states where most national production occurs. Pará, the northernmost state in the country, has both the largest reserves and the most production of copper in the country. Taken alone, Pará was responsible for 77 percent of the production of concentrated copper in 2018. Next was Goiás, with 15.1 percent, and Bahia, with 7.8 percent of production (ANM, 2020b).

Grades for the production of copper concentrates (see Table 2) are close to those expected for viable projects, with Bahia (despite its lower quantities) producing copper concentrates of higher quality.

Table 2. Production of Copper Concentrates, 2018

	Processed (t)	Contained Copper (t)	Average Content (% Cu)
Copper	**1,303,493**	**385,762**	**29.59**
Pará	972,185	297,061	30.56
Goiás	243,129	58,582	24.10
Bahia	88,179	30,119	34.16

Source: ANM (2020b).

7 According to a specialized website for copper investors (https://investingnews.com/), the average grade of copper ores in the 21st century is below 0.6 percent copper. In Chile, grades declined from 1.41 percent to 0.65 percent between 1999 and 2016 (Cantallopts, 2017).

8 According to the Copperalliance website, based on U.S. Geological Survey data (https://copperalliance.org/about-copper/long-term-availability), since 1950 there has always been, on average, 40 years of copper reserves worldwide; however, not all of those reserves are accessible for economic exploitation.

Even though it is exported in smaller quantities than other minerals, copper is an important part of Brazil's portfolio of mineral exports (Table 3). In 2018, copper accounted for over 7.5 percent of total exports for the top 11 metallic substances (ANM 2019).

Table 3. Export Value of Copper, 2018

Material	Product Type (US$FOB)				Total (US$FOB)
	Primary Goods[a]	Semi-manufactured[b]	Manufactured[c]	Chemical Components[d]	
Total	**23,572,410,418**	**15,224,787,818**	**6,974,733,995**	**671,740,941**	**46,443,673,172**
Copper	2,640,445,360	402,133,984	455,103,276	9,990,786	3,507,673,406

Source: ANM (2019).
Database: Ministry of Development, Industry, and Commerce. [a]Copper ore and its concentrates. [b]Anodes and Cathodes and their elements of refined copper, unwrought, and alloys. [c]Pipes and fittings, rolled copper, bars and wires. [d]Copper oxides and hydroxides, copper chloride, and other copper chemicals.

Export destinations vary according to the type of copper product. Germany (15.4 percent), Bulgaria (12.0 percent), Sweden (10.2 percent), and China (10.0 percent) were the main importers of Brazilian copper concentrates in 2018.[9] China is by far the main destination for semi-manufactured and manufactured products, accounting for 95 percent of purchases in 2018 (UN Comtrade, 2018).

Although in 2018 Brazil's exports reached US$3.5 billion (FOB), the country also imports copper. Comtrade data shows that, in 2018, Brazil imported US$2.3 billion (FOB) in copper, with half (US$1.4 billion) being semi-manufactured products. Chile is by far Brazil's main provider (79.6 percent), followed by Peru (15.7 percent).

As for concentrates, in 2018, Brazil's main suppliers (based on monetary value) were Peru (54.8 percent) and Chile (45.1 percent) (UN Comtrade, 2018). One of the main consumers is Paranapanema, the only copper smelter in Brazil.

Understanding the reasons behind these transaction patterns involves engaging in a growing debate on the verticalization (or lack of it) of the copper industry in Brazil. While the political class tends to encourage vertical integration (i.e., producing refined copper to capture a big part of the value chain), mining firms do not find it economically interesting because it is capital intensive and generates a number of residues that are difficult to handle.[10] Moreover, there is an understanding that Brazil does not have a big enough market to absorb extra production of refined copper and that it faces competition from well-established smelting industries in countries like China and Germany. Finally, the cost of production in Brazil makes importing refined copper cheaper than producing it internally. As stated by a manager from a mining firm interviewed for this study (translated):

> "Concentrating copper is the only segment that creates value in mining. Once it reaches the smelter, the capex is cheaper (30 to 50 percent of mining), but the remuneration from

9 In 2019, Germany remained the main importer (25 percent), followed by China (13 percent), Poland (13 percent), and Spain (10 percent).

10 Paranapanema, the only smelter in Brazil, resulted from an old, public, integrated Brazilian mining firm that had been split up in the 1980s after privatization.

treatment and refinement is lower, around 10 percent of the cathode's price (...) Mining has a bigger margin in relation to the final price of copper. The smelter gets between 0 and 10 percent of the final price and the stage from smelting through the final product, the production of the copper rebar, gets 2 to 4 percent."

Copper Production: Few Regions, Few Companies

In Brazil, copper production is concentrated not only in a few regions but also in a small number of firms. Pará, the northernmost state in the country, has both the largest reserves and highest production of copper in the country. Pará was responsible for 77 percent of concentrated copper production in 2018, followed by Goiás with 15 percent and Bahia with 8 percent (ANM, 2020b).

The largest share of production comes from three firms, two of which are responsible for more than 70 percent of production: Vale S.A. and Salobo Metais S.A. (which is a subsidiary of Vale). Vale is a true mining giant. In addition to being the third largest firm in Brazil, it is also the fourth largest mining firm in the world. Salobo has one of the largest deposits of copper ever found in Brazil and is now in the second round of expansion (Salobo III). Table 4 lists the main copper mines and refining plants in Brazil. Table 5 lists the main copper-producing (concentrates) firms.

Table 4. Main Copper Mines and Refining Plants in Brazil, 2018

Mine/Plant	Discovered	Start of Production	City/State	Company	Parent Company	Goals
Sossego	1997	2004	Canaã dos Carajás, Pará	Vale S.A.	National publicly traded company	140,000 t/year Cu
Salobo	1974	2012	Marabá, Pará	Salobo Metais S.A.	Vale	200,000 t/year Cu
Chapada	1973	2007	Alto Horizonte, Goiás	Mineração Maracá, Indústria e Comércio S.A., Yamana's Gold subsidiary	Canadian. Bought by Lundin (also Canadian), a publicly traded company	65,000 t/year Cu
Complexo Pilar (R22W MSB – Subterrânea) and Vermelhos	1874	1974 1979 2018	Jaguarari (Pilar) Curaçá e Juazeiro, (Vermelhos) Bahia	Mineração Caraíba S.A.	Ero Copper Corporation, Canadian publicly traded company	Integrated operations of mining and refining plant 90,000 t/year of Cu; In Vermelhos, 27,500 t/year of Cu
Caraíba Metais	1974	1982	Dias D'Ávila, Bahia	Paranapanema S.A.	Domestic. Publicly traded company	Refining plant, 280,000–300,000 t/year of refined copper (2018). Finished products are made in São Paulo and Espírito Santo.
Antas	2011	2016	Curianópolis, Pará	AVB Mineração Ltda.	Oz Minerals, Australian publicly traded company	Mining and concentration, 12,000 t/year Cu

Source: Adapted from Fernandes and Monteiro (2016) and DNPM (2017b).

Table 5. Main Copper-Producing Firms, 2018

Company	State	Participation Index (%)*
Salobo Metais S.A.	PA	53.76
Vale S.A.	PA	20.67
Mineração Maracá Indústria e Comércio S.A.	GO	16.42
Mineração Caraíba S.A.	BA	6.33
AVB Mineração Ltda.	PA	2.52

Source: ANM (2020b).
* Participation (%) of the firm in total traded value of the copper production.

In terms of size, three of the seven main copper-producing mines are considered large (annual run-of-mine above 1 million tonnes), three are considered medium (above 100,000 tonnes and below 1 million tonnes), and one is considered small (below 100,000 tonnes). Six are open pit and one, in Bahia, is underground (ANM, 2020b).[11]

Market Trends for Copper in Brazil and Worldwide

Before COVID-19 hit all markets, the Brazilian mining sector was still trying to recover from the drop in commodity prices over the previous few years that was linked to China's slowdown and the recent trade conflict between China and the United States. In Brazil, challenges were compounded by slow economic growth for the previous seven years, affecting those industrial sectors that use copper, such as the automotive and construction sectors.

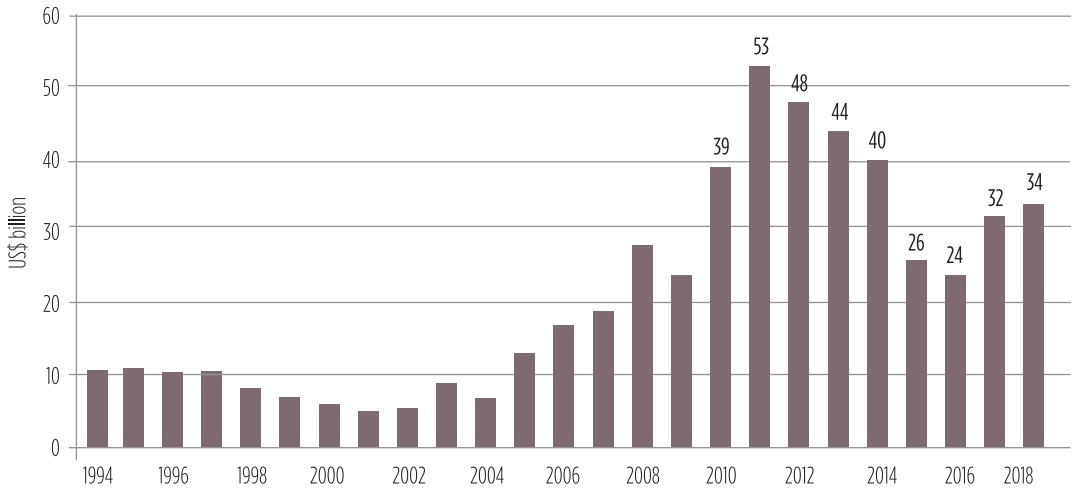
Mining production, which had been growing since the early 2000s, started to decline in 2011 (the point of highest growth) along with many other sectors within the Brazilian economy. The sharpest fall took place after 2014, when the country entered a recession (Figure 4). Also, private investments in the mineral sector, which had been growing since 2007, started to decline from 2012 onwards (Figure 5).

Mesquita, Carvalho, and Ogando (2017) noted that the main difficulties mining companies need to overcome are oversupply, lower market prices, falling return margins, and greater competition in the foreign market. In recent years, those challenges have been affecting the Brazilian mining industry.

Despite this inauspicious scenario, production (including copper) has been recovering since 2015. The COVID-19 crisis presents a totally new scenario for the mining industry in the context of falling prices (Figure 6). However, the S&P is making positive projections for copper prices in the future, with forecasts for US$6,005 per ton in 2019 to US$6,425 per ton in 2022 (Sappor, Rutland, Rodwell, et al., 2020).

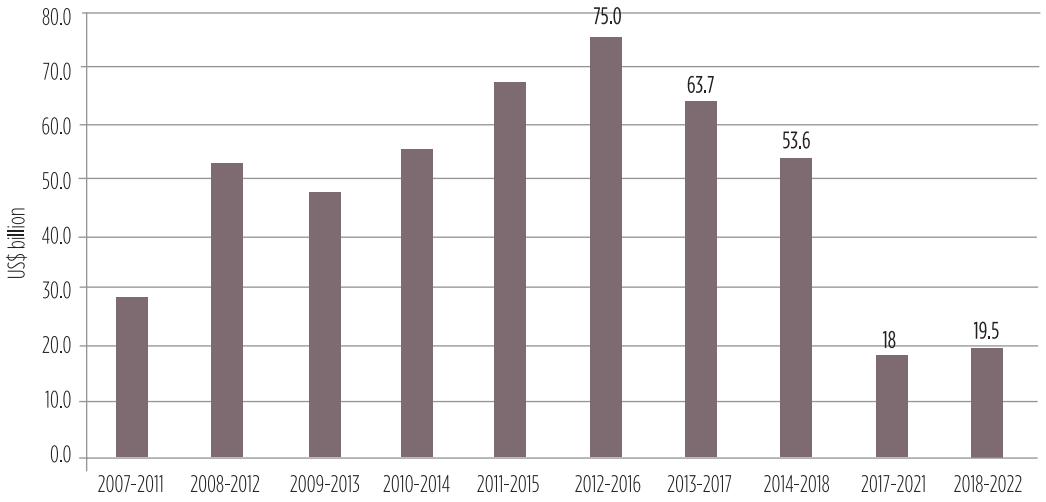
11 Though other firms in Brazil produce copper, their production is smaller and usually a by-product of their production of other minerals.

Figure 4. Mining Production in Brazil



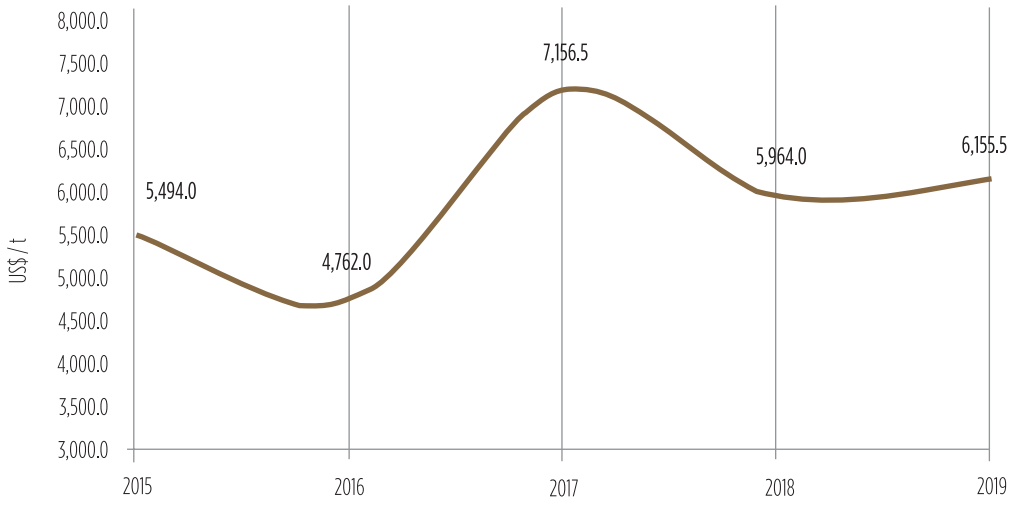
Source: IBRAM (2019a).
* Considers all extraction sectors, except oil and gas.

Figure 5. Investment in the Mineral Sector



Source: IBRAM (2019a).

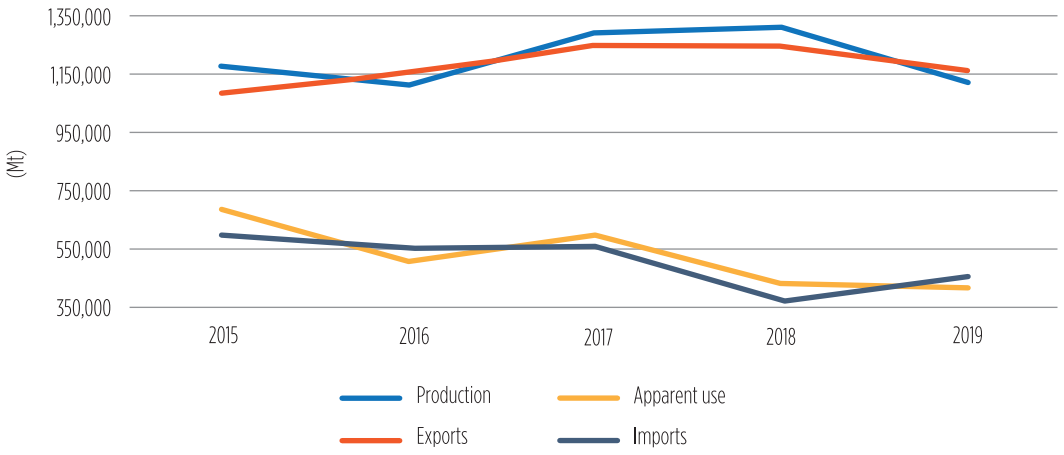
Figure 6. Copper Price



Source: London Metal Exchange.

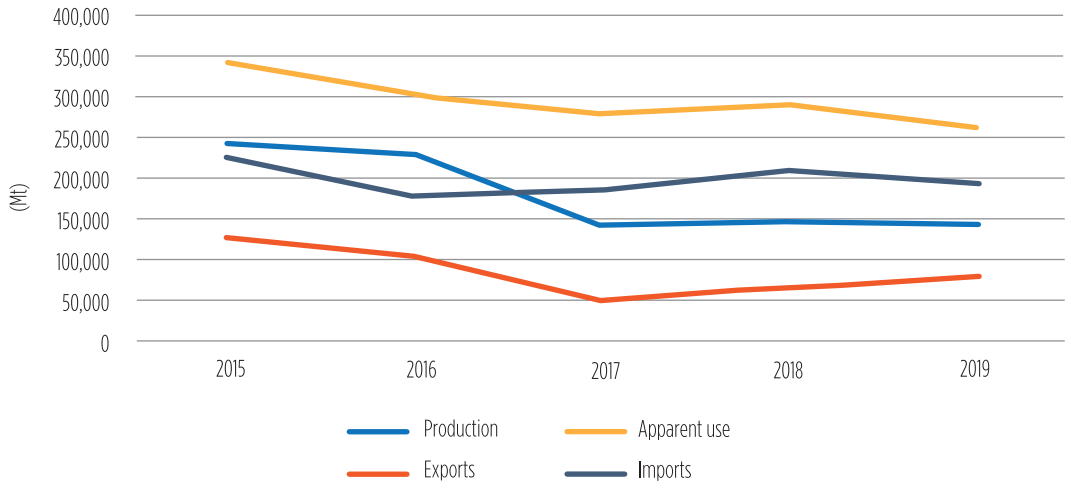
Figures 7 to 9 provide a general view of copper market performance for the period 2015–2019. They show a fall in production and exports of concentrate and other types of copper between 2018 and 2019, just after a period of increase (or, at least, stability).

Figure 7. Overview of Market for Copper Concentrate in Brazil



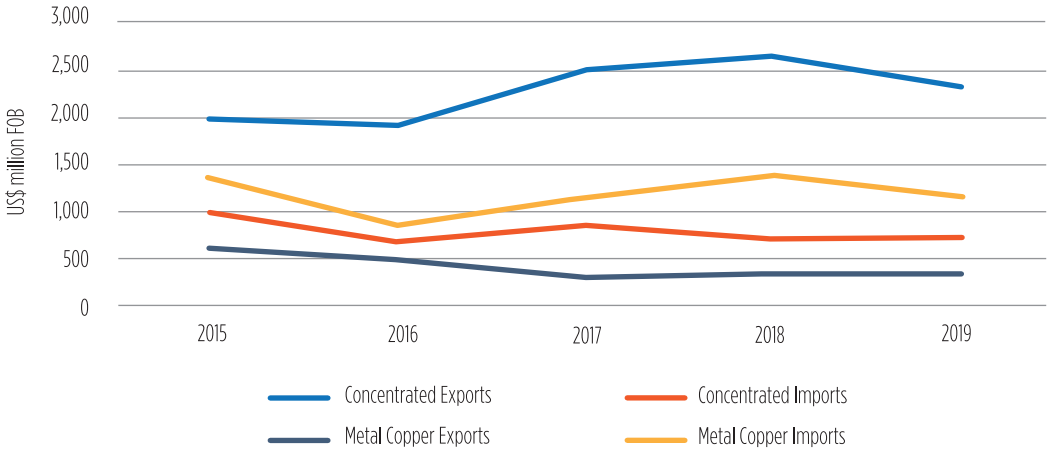
Source: Production in total tons, ANM (2019 and previous years); copper ores and concentrates, Comtrade cod. 260300, consulted on June 30, 2020.
Notes: Production figures were not available for 2019. Estimates of production and apparent use were based on average relative values between production and exports.

Figure 8. Overview of Market for Semi-manufactured and Refined Copper in Brazil



Source: SGM (2020), Paranapanema S.A., and UN Comtrade (various years) for copper mattes, unrefined/anodes, and refined and copper alloys: Codes 7401 to 7403, consulted on June 30, 2020.
Notes: Does not include recycled copper. Production data for 2017 and 2018 are preliminary.

Figure 9. Monetary Value of International Trade



Source: UN Comtrade for copper mattes, unrefined (anodes), and refined (cathodes and copper alloys), codes 7401 to 7402.

Even if the economic crises and price fluctuations had not taken place, historically there has been a deficit between copper production and global demand, which has maintained the attractiveness of the sector for both production and exports. At times when domestic demand decreases, external demand tends to compensate, thereby driving large amounts of copper production toward export markets.

The Brazilian Copper Association (ABCobre) studies copper market trends and frequently reports that copper has good growth potential. The association states that, in addition to the traditional applications for copper, such as the machine industry, electricity, and civil construction, other uses have been appearing in new sectors, such as renewable energy and electric vehicles (which consume 30 percent more copper than traditional vehicles). ABCobre argues that there is a dearth of mining projects ready to start extracting copper to be used as a traditional electricity conductor, and that companies that are willing to invest in such projects would be making a good business decision. However, the authors see reason to be cautious with ABCobre's optimism because final copper consumers have been looking into cheaper substitutes and have found that aluminum is an attractive option with similar conductive properties at a fraction of the cost of copper.[12] Such a transition from copper to aluminum (if it happens) will not be swift and demand for copper seems secure at the moment, in turn implying a risk of shortages given that production has been stabilizing.

A New Copper Rush to Brazil?

The effect of market recovery in 2016 was quickly felt in Brazil. The ANM's Brazilian mineral summary for 2017 (DNPM, 2017a) states that (translated), "The Brazilian industrial copper sector, including both semi-manufactured and processed products, had net revenue of US$6.5 billion, generated taxes of US$865 million, produced foreign exchange of US$2.8 billion as a result of exports, and created 4,208 direct jobs. With regards to copper extraction and concentration, the contribution from mining to the local economy (known by the accronym CFEM in Portuguese) brought income of 124 million Reais for the country."

Despite a decline in the number of projects due to the recent crises, the copper industry has bounced back over the past couple of years and some new initiatives have been announced. In 2017, there were 413 new mining titles awarded for mining research in copper. At the time of writing, Nexa Resources, a joint venture between Votorantim (Brazil) and Iamgold (Canada), was in the process of obtaining an environmental license to open a new multimetal mine in Rio Grande do Sul. Representatives of the project interviewed for this report stated that Nexa was planning to reopen a closed mine in Camaquã to extract zinc, copper, and gold. In Rio Grande do Sul, the firm Aguia Resources bought a project called Primavera next to Camaquã that contains high-grade copper areas. The Primavera project would complement other copper and phosphate projects already underway. To be closer to those new investments, the firm moved its office from Belo Horizonte in Minas Gerais to Porto Alegre, the capital of Rio Grande do Sul (Aguia Resources, 2020). Caraíba Metals expanded its activities in Bahia using the Vermelhos mine to enlarge the mining complex in the area. Canadian firm Lundin bought the Chapada mine from Yamana Gold in April 2019.

Oz Minerals (Australia) gained a foothold in the copper mining area of Carajás by buying AVANCO and its Antas mine in Pará. The specialized magazine *Mining* named Antas one of the world's highest-grade copper mines (Basov, 2017). Oz also acquired the Pedra Branca advanced copper project in the neighboring province of Gurupi and an option to buy the prospective Pantera project from Vale (Portela, 2019). By November 2019, a series of interlinked agreements between

12 The source for this view is interviews carried out by the authors with copper consuming firms and with a finished copper wholesaler.

Oz and Vale allowed Oz to use Vale's vast infrastructure already installed in the Carajás area to move the mineral from mine to ports and to announce the construction of the Pedra Branca mine. Lara Exploration (Canada) announced an option to buy 100 percent of a copper project in Planalto, which includes several iron ore, copper, and gold mining rights in the vicinity of the Sossego copper mine (owned by Vale) and the Antas copper mine (owned by Oz) (*Mining News,* 2019a). After much uncertainty, Mineração Vale Verde's Serrote da Laje project was expected to start operating in the municipality of Caraíba in the state of Alagoas. Sold by Aura Minerals (Canada) to Appian Capital Advisory (a venture capital company based in London, England, with offices in South Africa and Canada (Conexão Mineral, 2018), Vale Verde (a wholly owned subsidiary of Aura Minerals) recently completed its detailed plan for the flotation process that will be used in their project (Vale-verde.com, 2020). Finally, Vale has resumed some of its projects to expand copper production in Carajás. Table 6 summarizes the main copper projects in Brazil.

Table 6. Main Copper Projects in Brazil, 2017–18

Project Name	Beginning of Production (Expected)	City, State	Company	Parent Company	Goals
Projeto Serrote	2021	Craíbas, Alagoas	Mineração Vale Verde	Appian Natural, London. Investment Fund	Expected production: 100,000 t/year Cu
Salobo III	2022	Marabá, Pará	Salobo Metais S.A.	Vale, national publicly traded company	Expected increase of 30,000 to 40,000 t/year Cu
Cristalino	2023	Curionópolis, Pará	Vale S.A.	National publicly traded company	Expected production of 80,000 to 100,000 t/year Cu
Alemão	2024	Parauapebas, Pará	Vale S.A.	National publicly traded company	Expected production of 60,000 to 70,000 t/year Cu
Caçapava do Sul	2023	Caçapava do Sul, Rio Grande do Sul	Nexa Resources and Iamgold (Joint Venture)	Votorantim Group, privately owned Brazilian holding company	5,000 t/day Cu
Big Ranch, Canhada, Primavera, and Andrade	under analysis	Rio Grande Copper Belt (Lavras, Caçapava do Sul), Grande do Sul	Aguia Resources/ Referencial Geologia Mineração e Meio Ambiente	Australian publicly traded company	under analysis
Pantera	under analysis	Urulândia do Norte, Pará	Oz Minerals	Australian publicly traded company	under analysis
Pedra Branca (underground)	under analysis	Curianópolis and Parauapebas, Pará	AVB Mineração Ltda.	Oz Minerals, Australian publicly traded company	1.2 million t/year ore

Project Name	Beginning of Production (Expected)	City, State	Company	Parent Company	Goals
Liberdade	under analysis	Carajás, Pará	Lara Exploration Ltda. in JV with Codelco do Brasil Mineração Ltd.	Publicly traded Canadian company	under analysis
Planalto	under analysis	Carajás Mineral Province (Curianópolis and Canaã dos Carajás), Pará	Lara Exploration Ltd.	Publicly traded Canadian company	under analysis
Pilar	under analysis	Jaguarari (Pilar), Bahia	Mineração Caraíba S.A.	Ero Copper Corporation, Canadian publicly traded company	n.a.

Impact of Scale on Vertical Integration

The trend among mining firms is to grow through mergers and acquisitions. In 2018, there were 14 mergers in the sector, five involving foreign companies acquiring Brazilian companies and five involving foreign companies acquiring other foreign companies based in Brazil (KPMG, 2019a). Although mergers showed a downward trend in 2019, declining 30 percent in the first half of the year compared to the same period the previous year, this was more due to the major crisis faced by the sector after the Brumadinho disaster than to changes in the patterns and trends established previously (KPMG, 2019b).

What fuels this process is the constant search for new reserves given the exhaustion of old mines in Brazil and in other regions of the world. In Chile, for instance, there is a clear perception that, despite its abundance, natural resources are finite. As stated by the president of Codelco at a conference held in Antofagasta in May 2019, "Copper supply is expected to start to decline in 2022, resulting in a deficit of 4 million tonnes by 2028" (*Mining News*, 2019d). This decline will be caused by many factors, among them, the depletion of Chilean reserves. As pointed out in the article, "ore grades from Codelco mines decreased by 14 percent between 2014 and 2018, forcing the company to process more volume to obtain the same amount of mineral." Furthermore, water scarcity has restricted production and extraction (copper processing requires intensive water usage) in several parts of the Chilean territory. In other countries, the depletion of mines and the low grade of the reserves threatens mining activity overall and increases production costs.

Not surprisingly, the use of secondary mineral (waste from the primary processing) and any activity geared toward recovering mining material from mining waste has been emerging as a strong global trend. However, the recovery of metal from these substances is still too low to satisfy growing markets. In Brazil, as a result of constant mineral research and new projects, new reserves might be discovered in other regions of the country, enlarging and strengthening local productive capacity and, more importantly, reducing market concentration.

Junior firms play an important role in this context, as they are often responsible for prospecting and discovering new mineral reserves, as well as securing investors to carry out research. Once a reserve has been proven and the financial feasibility of the project has been clarified, then juniors aim to sell the project to a large mining firm for a profit.[13]

Challenges and Innovation Needs

Mining has always been an industry with growth potential in Brazil. The country's vast territory and mineral reserves make it a promised land for investors expecting copper demand to continue in the medium and long term. To realize this potential, however, it is important to overcome several challenges.

In Brazil, copper production follows the pattern of mining in general in the country, with a marked presence of venture capital for large investments. Until a mine becomes productive, there is a long cycle that begins with prospecting, continues through mineral research, extraction planning, mine design, then extraction of the mining material, processing of the material, and environmental recovery during the extraction period and after the mine's closure. From the beginning to the end of this long cycle, 10 or 20 years could elapse. According to IBRAM (2018), there is a rough calculation showing that of 1,000 identified geological anomalies, 100 sites are explored with diagnostic drilling, of which 15 mineral deposits are found, and then up to four considered for extraction. After years of studies, investments, and legal dealings to obtain the right permits at each stage, the whole process can result in just one or two actual mines.

Moreover, despite the richness of Brazilian soil with regards to mineral resources, much of the territory is unavailable for exploration. At a national mining event (attended by this report's authors), a large mining company pointed out that, of a total of 852 million hectares of Brazilian territory, only 231 hectares (or 27 percent) are available for exploration. A total of 170 hectares (approximately 20 percent) are preserved areas or Indigenous reserves. Brazil has far fewer investments per square kilometer than other countries in Latin America (12 times less than Chile and Peru, six times less than Colombia, and five times less than Argentina) (Azevedo, 2019).

In Brazil, many reserves are located in remote regions with poor infrastructure and/or in the vicinity of land owned by Indigenous groups or environmental reserves, making mining even more complex. Additional challenges include impinging on political debates on topics that are becoming highly controversial in society broadly, such as biodiversity, environmental preservation, and cultural and human rights for Indigenous communities vis-à-vis the potential for material gains that could be brought by the mining process to local communities and governments. Other obstacles include the high cost of production due to the so-called Brazil cost (Custo Brasil), which refers to the high

13 In a presentation at the ADIMB FORUM for Mineral Exploration in August 2019, ADIMB stated that 55 mining companies operating in Brazil are listed on the stock exchange. Among them, several junior companies mainly focus on exploration. The majority of those companies (37 of 55) are listed on the Toronto Stock Exchange. In 2019, there were a total of 12,369 research permits, of which 3,899 were for non-ferrous metals, a category that includes copper. Nevertheless, there is still a massive gap between investment in exploration in Brazil compared to other countries: Brazil accounts for only 0.7 percent of global investment in mineral exploration and, on average, for only 13 percent of total projects under drilling activities in 2019 (Bastos, 2019; Carvalho, 2019).

operational costs related to inefficiencies within institutions, logistics, bureaucracy, and taxes specific to Brazil. Combined with low demand for manufactured copper, the Brazil cost makes Brazilian firms opt to export concentrated copper instead of investing in transporting it to a smelter within the national territory. According to mining firms and their suppliers (reported in secondary material and also during exploratory interviews for this report), it is cheaper to export than to transport concentrated copper to a smelter within the vast Brazilian territory. That also helps explain the relatively high levels of imports of refined copper; for tax and logistical reasons it is cheaper to import than to produce. This situation evidences a clear opportunity for public policies to be designed to streamline processes that allow for better national integration between different links of the copper mining value chain.

Still linked to the Brazil cost and mainly related to bureaucracy, there are difficulties obtaining environmental licenses. While licensing requirements are necessary and vital and can represent a business opportunity for many consulting firms, long wait times tend to delay the operation of a project for years, increasing costs and, in some cases, resulting in losses for companies. A sector leader—the president of the Brazilian Association of Mineral Research Companies (ABPM from the Portuguese)—spared no criticism of the Brazilian regulatory environment: "the country is light years behind in mineral research compared to other producing countries, such as Canada, Australia, Peru, Colombia, and Chile, which invest in the development of markets, strategic trade agreements, and internal knowledge." On the other hand, Brazil's bureaucracy and lack of infrastructure discourage investors. "We must learn from other countries and seek agility in granting permits and licensing, moving away from bureaucracy, bringing fiscal stimulus measures for research and development (R&D) in technology, and practicing investment partnerships" (Goldberg, 2019, translated by the authors).

Indeed, according to Salomão and Veiga (2019), the average time to obtain a mining license for extraction in Brazil is 12.5 years, with 28 percent of the grants taking more than 20 years to complete. Interviews at a regional ANM office tell a more complex story. We learned that part of these delays is also due to the mining companies themselves, which sometimes interrupt a project, delay delivery of documentation, or request extensions to submission deadlines. Either way, finding ways to ensure adequate analysis in a timely manner to reduce economic risks for companies remains a challenge for the sector. With regards to labor, the country's educational challenges and the generally low level of formal qualifications of Brazilian workers are well documented and this is no different in the mining industry. Fortunately, the sector currently has enough resources, including specialized training institutes, to mitigate deficiencies within the labor force. However, during exploratory interviews for this report, key informants explained that it is becoming increasingly difficult to attract top talent to the mining sector, particularly young people fresh out of university. The causes for this lack of interest need further investigation, but some anecdotal evidence points to the negative image of the mining sector linked to its environmental impact.

A crucial challenge for the mining industry in Brazil—and the world—has been the ecological and human disasters at Mariana and Brumadinho. These disasters had enormous effects in terms of environmental damage and the number of people injured or killed. The environmental disaster at Mariana in 2015, where the dam managed by Samarco (owned by Vale and BHP) broke, placed companies under stringent scrutiny, revealing the risks posed by mining operations and the costs

involved in recovering from this type of accident. A whole city was destroyed by contaminated mud, rivers were polluted, and several people died. Damages were almost impossible to calculate and created the need for reconstruction plans never seen before in the country. In the following months and years, other mining firms had similar problems and their productive systems and waste management operations became the target of protests and of criticism on social media.

A few years later, in January 2019, at Brumadinho, the dam managed by Vale buried most of the city and killed over 230 people. This brought the mining sector's legitimacy crisis to unprecedented levels. The first building buried was Vale's directory office in Brumadinho, highlighting the fact that everyone was at risk, both Vale staff and the local communities. Regulating agencies strengthened oversight, new laws were passed demanding the decommissioning of traditional dams, several mines were paralyzed, and ultimately national production of (mainly) iron ore was affected, which in turn affected international prices.[14]

The size of firms, the amounts transported, waste management challenges, water consumption, disaster prevention management, and other issues mean that local communities are on high alert wherever mining companies operate, making it necessary for firms to prove their value and safety. Looking back at the challenges faced by the mining industry, it is evident that firms need to innovate with regards to cost management so that they are less dependent on commodity prices and can protect themselves from price fluctuations. However, recent environmental and human disasters show that they also need to innovate with regards to environmental and social risk management because the costs of not doing so may make the mining industry unsustainable in the near future.

A recent study on innovation in Latin America suggests that even if the need to innovate is widely recognized, Latin American firms lack consistency and strategic focus when it comes to deciding on policies and action (Deloitte, 2017). The literature tends to refer to mining activity as conservative, with little interest in innovation. Nonetheless, some researchers (e.g., Marin, Perez, and Navas-Aleman, 2015) have looked at the dense network of input suppliers and service providers and have been more successful in finding cases of innovation. In particular, previous studies on mining innovation by suppliers in Latin America (see Figuereido and Piana, 2016; Pietrobelli et al., 2018; Stubrin, 2017; Urzúa, 2011) have informed the present study.

Mesquita, Carvalho, and Ogando (2017) highlight that the most promising new technologies being incorporated in the traditionally less intensive technological sectors, such as mining, tend to be the ones with greater transversality and linked to the concept of Industry 4.0[15]: diffusion of big data, internet of things, additive manufacturing digitization, interconnectivity systems with a focus on developing more efficient systems, and production processes. At the same time, some large mining firms are challenging conventional wisdom and investing in innovation by incorporating new technologies in areas like big data, industrial automation, new materials, and new management techniques.

Vale announced its acquisition of autonomous trucks and, at least in one mine, it chose to install conveyor belts to substitute trucks for long (but repetitive) journeys. One example is the S11D Complex in Carajás (iron extraction), where traditional trucks were replaced by diggers, mobile

14 Vale suffered several losses when it stopped producing at Brumadinho, but with the scarcity of iron in the market, prices rose, allowing the company to offset these losses through production from other iron mines still in operation.

15 Industry 4.0, or the fourth industrial revolution, enhances the use of computers and automation with smart, autonomous systems that use data and machine learning.

crushers, and conveyor belts to transport all of the mining output to the processing unit. Thanks to that new arrangement, the firm reduced its diesel consumption by 70 percent and purchased fewer tires, which in turn reduced waste associated with old tires and pollution from engine oils and other substances required for truck maintenance.

Vale's Mineral Development Center also researched the industrial use of bioleaching, a technique that uses bacteria to stimulate the extraction of copper (Vale, 2015, cited in Figuereido and Piana, 2020).

According to Mesquita, Carvalho, and Ogando (2017, p.338, translated by the authors),

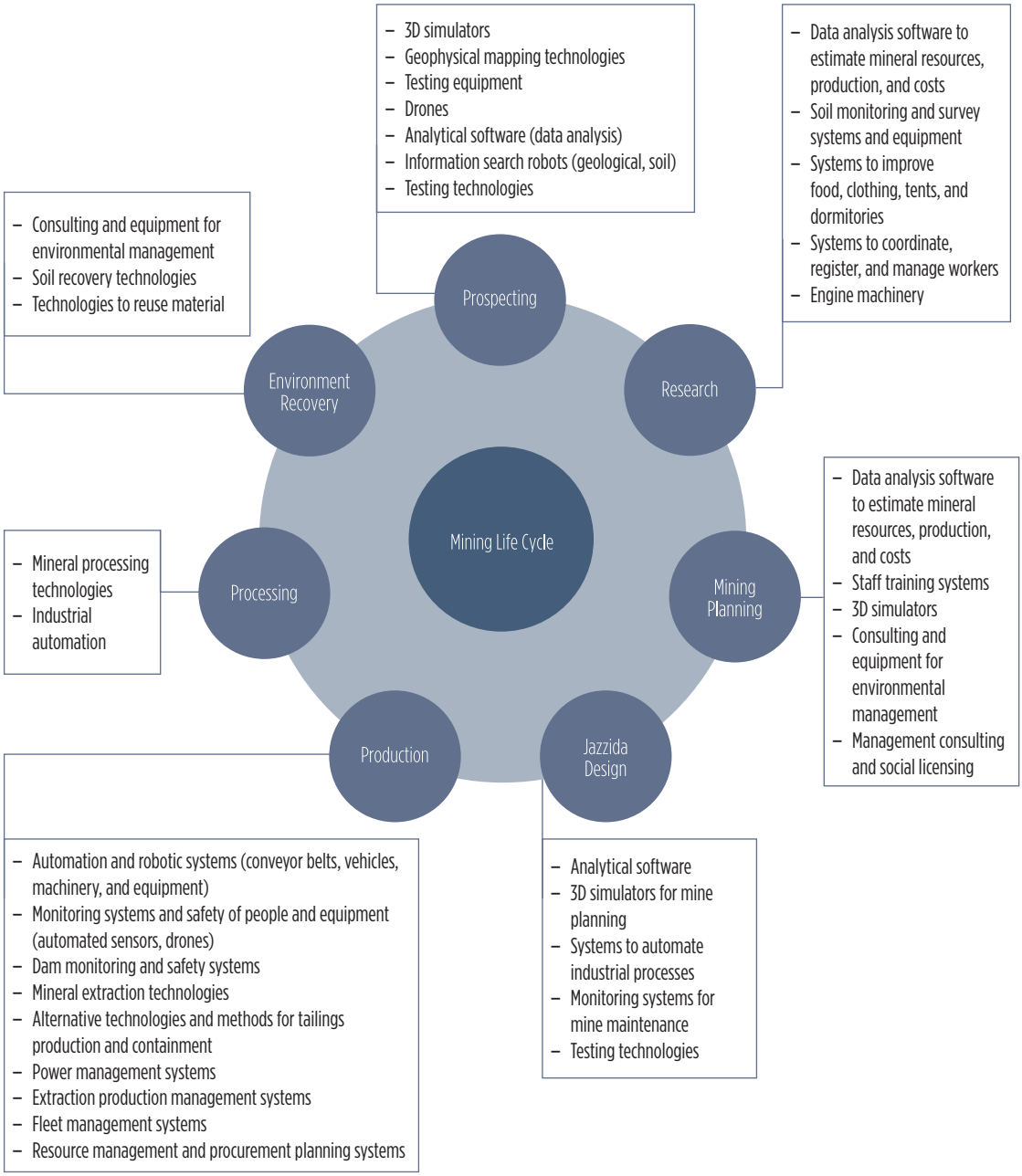
> The main research areas involved in the development of advanced manufacturing and most of the technological developments in advanced manufacturing are concentrated in the following elements of the mining process: sensors and monitoring, including new methods for low-cost data measurement, real-time process analysis, and integration with control technologies; control and automation systems involving rapid integration between the various production mechanisms and business and simulation models; digital systems for simulation and 3D visualization capable of allowing product design and definition of production methods simultaneously; and digital platforms, standards, and communication protocols to support the connection between design and production, and data integration and digital and real systems.

In sum, innovation seems to be the only safe way to increase companies' production and profitability and to recover a positive public image for the mining sector.

The extent to which this movement toward innovation is taking place in Brazil, especially outside the circuit of large mining companies and international suppliers, is one of the main issues dealt with in this study. A leader of the Minas Gerais Chamber of Mining stated that one of the sector's main weaknesses is the lack of technology transfer policies available in the mining industry, providing a clear opportunity for government to develop public policies to support the innovation processes of the Brazilian mining sector. Figure 10 shows opportunities for innovation along the life cycle of a mine, from research to mine closing.

In Brazil, the maturity of the mining sector attracts a wide range of suppliers. Copper mining is concentrated in the country's north, but other mining activity happens all over the country, with particular emphasis on the Iron Quadrilateral (*Quadrilátero Ferrífero* in Portuguese) in the state of Minas Gerais. Although Minas Gerais does not produce copper, the state has the longest tradition of mining in the country and the most experience, having been active since colonial times. Minas Gerais began its mining history with gold and silver and expanded to other minerals over the years. The state also hosts large numbers of suppliers to the mining industry. There was a generalized perception among this study's key informants that the north of the country will in time replicate Minas Gerais' deep network of suppliers and service providers, but there are clearly some barriers to overcome and some clear roles for innovation policy in the mining sector to support the development of these networks.

Figure 10. Mining Life Cycle and Opportunities for Innovation



Source: Authors' based on fieldwork interviews and secondary sources.

The spread of mining activity in Brazil created opportunities for a vast supply chain to flourish in diverse areas, such as machines and equipment for mining; trucks and conveyor belts for heavy cargo; technology services and management; logistics, transport, and distribution; explosives; and energy transmission, among others. In all cases, adaptations to local conditions, including remote locations with difficult access, are required.

However, the dense web of suppliers and service providers is still mostly composed of multinational companies, with few Brazilian companies represented among Tier 1 suppliers. Multinational companies tend to dominate the supply chain with their well-developed technological capabilities, but also—and this is crucial—their non-technological capabilities in areas such as finance, marketing, distribution channels, management, and contacts with markets abroad. For instance, multinational companies protect their brand and create contractual obligations to guarantee their exclusivity in providing machinery by, for example, limiting the ability to use cheaper replacements instead of authorized branded machines. Key informants also report that local equipment is often expensive for the quality, pushing companies to buy the international brands.

There is more scope for large national consultancy firms, engineering firms, and laboratories to participate, but large foreign companies still dominate. The results of national laboratories are accepted, but clients often demand to see additional (or identical) tests carried out by international testing centers.

Our desk research suggested that most innovation opportunities for national companies are in the pre-extractive phases (prospecting, research, and extraction planning) and in the final stages, when the mine is decommissioned. In those early and late stages, local knowledge is more valuable and barriers to entry (including capital) are smaller. However, as this study advanced, it became clear that in Brazil, innovation opportunities for domestic suppliers abound in all stages of the value chain.

An important finding from the exploratory phase of this research was that the mining processes for iron and copper are similar and highly intertwined, often carried out by the same firms and supplied by the same suppliers. This proximity makes it very difficult to isolate innovations by suppliers that are specific to copper since many innovations benefit the mining sector in general.

When considering the innovation possibilities and the density of the supply chain together, it could be argued that the situation is ideal to promote not only better competitive conditions for the whole mining sector, but also an improvement to its image nationally and internationally. Important questions that guided this study during fieldwork included whether local (domestic) suppliers would have the capacity to develop new solutions and whether they operate in an enabling environment that favors those developments. The next section analyzes the institutional environment and the legal framework for mining.

Legal Framework and Institutional Environment

Shifts in the Political Landscape

This study was carried out in the middle of a shift in the political landscape. The previous two Brazilian federal governments had been inclined to lower barriers to private investment, which revived the debate on whether economic activity should be carried out in areas considered environmental or Indigenous reserves. In 2017, Michel Temer's government tried to liberate the RENCA (National Reserve of Copper and Associated Materials) reserve area between Amazonas and Pará for exploration. However, there was so much opposition that the Federal Government Decree issued by Temer had to be cancelled. RENCA occupies roughly 17,800 square kilometers (an area slightly

larger than Denmark). Besides threatening the integrity of the native forest, the decree would have allowed mining activity in nine environmental and Indigenous reserves.

A shift in policy toward protected areas began in 2018 when the country elected a president that is notably critical of the size of those reserves and defends the economic exploration of protected areas, most of them located in the Amazon region. The Bolsonaro government argues that Indigenous people could benefit from the natural resources by receiving royalties; however, the constitution gives the National Congress the power of approval for each project and demands a legislative decree, plus consultations with the affected communities (Senado Notícias, 2020). Complementary legislation is required to specify how those permits should be granted. As this has never happened, there is no legal mining activity on Brazilian Indigenous lands. However, in several of these demarcated areas, requests for mineral research were made before 1988, recently sparking intense debates about whether mining production should be expanded by entering those areas. Many Indigenous leaders and representatives of environmental non-governmental organizations stated their discontent with the expansion, whereas political leaders diverged in their opinions, with those close to the President being in favor while the opposition disagrees. After state prosecutors forbade the President from making federal decrees on this matter, the President presented a bill to congress to address the issue. However, the President of the Chamber of Deputies publicly announced that he would not put a mining project on Indigenous lands to a vote.

In short, the issue of expanding mining and other economic activities to protected areas is controversial and complex, and subject to numerous frictions with various sectors of society. As Mesquita, Carvalho, and Ogando (2017) highlighted, the mining sector is perceived as one of the industries that has the most negative environmental impact and is increasingly challenged to improve its environmental performance.

There is no clear consensus among mining companies about whether exploration in protected areas would be a safe route for the industry, and most of the institutions that represent mining have not taken a public stand on the issue. The Brazilian Mining Institute (IBRAM from the Portuguese) announced in the local press that the government did not listen to its proposals for the sector and that it awaits a political decision before making plans (Moura e Souza, 2020). It is no secret that some mining companies have supported the political campaigns of politicians who support relaxing protections and safety measures in mines (Angelo, 2020). Nevertheless, the mining sector is also perceived as being concerned about improving its image. It is unlikely the mining sector would support relaxing environmental regulations publicly. Mining companies are vocal about irregular prospecting, which they say is responsible for environmental damage unduly attributed to the formal mining sector. Thus mining companies have asked the government to regulate and control illegal mining. A study by the Amazonian Network of Georeferenced Socio-environmental Information (RAISG from the Portuguese) identified 2,312 illegal mines in the Amazon regions of Bolivia, Brazil, Colombia, Ecuador, Peru, and Venezuela. The study identifies 37 illegal gold mines on Indigenous lands, 18 of them in Brazil (*Mining News*, 2018c).

The debate on the expansion of areas for exploration is far from over and its evolution will depend on the composition of local political forces. In the meantime, measures have been implemented at institutional and legal levels to improve the sector's competitiveness, with varying degrees of success.

The Legal Framework

As in many countries, in Brazil the mining sector is extremely regulated. The ANM website shows that there are at least 35 federal bills, 42 federal decrees, 79 regulatory acts and standards related to mining activities, and 12 rules for the *mining manifesto* (the ANM-granted document that gives the holder ownership rights over the subsoil) , as well as 42 regulatory guidelines to reduce bureaucracy. Though not all regulations refer to metallic minerals, the number of laws and regulations is extensive and thus mining company complaints about the bureaucratic nature of the Brazilian regulatory system are justified.

Appendix 8 provides a list of the main federal laws (the table does not include state and municipal regulations) underpinning the regulatory framework for mining in Brazil. Including state and municipal regulations raises the total to a level that is almost impossible to comply with. The Federal Constitution establishes that mineral resources, including those in the subsoil, are assets of the union, meaning that mining firms have to obtain mineral rights and pay royalties to explore such assets. In Brazil, royalties are payed under CFEM (Financial Compensation for Exploiting Mineral Resources). The ANM is responsible for collecting CFEM. Royalty rates vary by mineral. For copper, the royalty rate is 2 percent of the gross sales revenue after trading taxes, but other rules apply for exports and for a firm's internal consumption. The collected royalties are allocated as follows: 60 percent to the federal district and the municipalities where mining takes place, 15 percent to municipalities affected by the mining activities (even if there is no mining activity in their municipality), 15 percent to states with mining production, and 10 percent to federal institutions (7 percent to the ANM, 1.8 percent to the Center for Mineral Technology [CETEM], 1 percent to the National Scientific and Technological Development Fund, and 0.2 percent for the Brazilian Institute of Environment and Renewable Natural Resources [IBAMA]) (IBRAM, 2020a; Szczesniak, 2015).

Decree-Law No. 227 of the Mining Code (1967) governs "all aspects of Brazil's mineral industry, from exploration to production and use of mineral resources [...] The Mining Code establishes the rights and duties of the holders of mining rights [...] A draft bill for a new regulatory framework for mining (Public Law No. 5807/13) was introduced in 2013 and continued to be reviewed in 2015. The bill would modify the Mining Code by creating the National Mineral Policy Council to assist the president in strategic decision making on minerals and by creating the [ANM], which would replace the National Department of Mineral Production [DNPM from the Portuguese] and be granted additional authorities, such as organizing public bidding for mineral rights" (Szczesniak, 2015).

The sector considered the 1967 code obsolete for a long time, but attempts to modernize it did not crystallize because of a lack of consensus on how to move forward. In 2017, during President Temer's regime, a proposal was made to rejuvenate the mining sector and the old mining code was updated in 2019. Updates included greater support for research by allowing the use of mining concessions as guarantees when seeking funds for projects. The updates also included stricter rules regarding mine decommissioning, making it an integral part of the mining process. In addition, time extensions for research were allowed in cases where the licensing process is delayed.

Also in 2017, a new project created the ANM to replace the DNPM as the main regulator for the sector. This was a long-awaited change. Another update that year altered all rules and percentages for the CFEM (this reform was less popular than the creation of the ANM, but it was accepted by

all parties). Taken together, these updates and reforms reduced uncertainty and created a better environment for investment in mining in Brazil.

Currently the Ministry of Mines and Energy (MME) manages the country's mineral resources by defining the main mining policies and issuing development concessions, while the ANM enforces the Mining Code, implements the code's legal provisions, and issues exploration licenses. Development concessions are valid up to the depletion of the mineral deposit and require an environmental license and adherence to an approved mining plan. Moreover, concessions require annual reporting to the ANM on activities, production, and sales. Further, the concession holder must restore degraded areas. Exploration licenses are issued on a first-come, first-served basis; can be held for up to three years; cover an area of up to 10,000 hectares depending on the mineral type and location; and require adherence to an approved exploration plan, payment of an annual fee, payment of the landowner's revenue, and compensation. The results of any work completed must be reported.

In sum, there is no doubt that in recent years there has been a concerted effort to modernize the mining industry by improving the regulatory framework. However, after Brumadinho, these efforts collided with an unprecedented movement of safety control and an unparalleled number of temporary closures: five months after the tragedy, 33 dams (belonging to Vale) were still closed in Minas Gerais. And Vale was not the only company that had to suspend activities for a while. In April 2020, countrywide, a total of 47 dams were still closed because they lacked a stability certificate (ANM, 2020c).

By means of a regulatory act, the newly opened ANM prohibited the construction of new upstream tailings dams. In addition, it ordered the elimination of all decommissioned upstream dams by August 15, 2021, and those still in operation by August 2023 (Cavallini and Erdely, 2019). The act covered 84 dams using the upstream method (considered to be of high risk) of 717 existing in the country. These numbers were subsequently revised and the time for decommissioning was extended to 2022–27. In addition, the target number for decommissioning has been reduced to 61 dams (from 84), as the criteria for classifying and counting dams was updated. At the time of writing this report, a variety of bills and amendments to create new regulations related to mining have been received by the National Congress. Some are related to security measures, while others are directed to compensatory economic payments, such as tax increases.

In addition, other constraints have been imposed on mining firms at the state level. For example, the State of Minas Gerais Law No. 23,291 (February 25, 2019) established the State Policy for Dam Safety. The law stipulates that creating or disposing of tailings and industrial or mining wastes using dams of any kind must be avoided whenever there is a better technique available. For a new dam to be authorized, the company must show that no other techniques, such as dry stacking, are viable. In the event of a disaster arising from non-compliance with the provisions set forth in the law, the administrative fine may be increased by up to 1,000 times. Pursuant to the law, one condition of environmental licensing for dams is presentation of an environmental bond to ensure social and environmental recovery in case of loss and for decommissioning.

The Institutional Environment

The density of Brazil's mineral production is supported by an extensive institutional network of at least 14 entities that have direct activities with the firms in the mining chain. Those entities focus

on different areas, such as lobbying, training and capacity building, research, and innovation. Some entities have a general responsibility, acting on behalf of the whole mining sector, others represent a segment of the chain, and still others (though they focus on safety and general regulations) promote value chain development through better regulation and policies. The institutional network is wide and reaches the whole national territory, but there are also organizations that operate at the state level, particularly in states that have large numbers of mining firms, such as Minas Gerais and Pará.

It is difficult to classify these organizations by relevance, as each has its own purpose and importance. Nevertheless, it is fair to say that some stand out either due to their leadership or to their role as regulators. On the public side, it is worth mentioning the Secretariat for Geology, Mining, and Mining Transformation (SGM), which is linked to the MME. The SGM is the entity primarily responsible for formulating public policies for the mining sector in accordance with the Federal Constitution and other federal laws, and in consultation with the industry.

The ANM, the industry regulator, is relatively new, having been created in 2017 as a result of a general movement for privatization and institutional modernization conducted in recent years, during which where several regulatory agencies were established. The ANM, the most recently created entity, enjoys more autonomy with regards to the government and has discretionary power over the sector. ANM technicians and managers can perform audits, apply fines, grant mining licenses, and order mines to be closed. In general terms, all strategic issues and official statistics about the sector come from the ANM and/or the MME via the SGM. After recent environmental disasters at Vale mines, the ANM acted as a mediator in the negotiations between the firm and the communities affected and took the lead in demanding new security norms to be applied in the sector. Besides the ANM, the IBAMA is linked to the MME and is the main regulator for environmental licenses. The IBAMA tends to be perceived as a bottleneck for mining development because of the time required to obtain environmental permits.

On the private sector side, IBRAM tends to lead since it represents mining firms and speaks for the mineral sector as a whole, defending company interests and supporting the creation of conditions that are conducive for business. IBRAM is one of the best-known entities in the sector even though it has faced criticism that it allegedly aligns its positions with those of the largest firms.

The Agency for the Technological Development of the Brazilian Mineral Industry (ADIMB from the Portuguese) is another important institution with regards to technical development. Finally, the ABPM represents mineral prospecting and mineral research.

Most of these organizations are located in Brasília, the country's national capital, and therefore a privileged spot for lobbying. Others are located in Rio de Janeiro, such as the ABPM.

It is worth highlighting the role of the Federation of Industries. In every state there are industrial federations that group together the owners of local firms. Many of these federations also host statewide mining chambers. The Mining Chambers of Minas Gerais and Goiás are particularly active.

For capital goods, the Brazilian Machinery and Equipment Industry Association (ABIMAQ from the Portuguese) is a nationwide business association for firms in various industries, including mining.

Apart from the ABIMAQ, the authors found no specific business or public–private associations comprising mining suppliers. Many Tier 1 suppliers are big competitors in global markets (e.g., Caterpillar, Komatsu, and Metso) and supply several sectors, not only mining. Even smaller, local suppliers do not work exclusively with the mining industry, taking part in a number of domestic value chains

at once. This is the reason most key informants interviewed for this study did not see an association of suppliers to the mining industry as a priority.

The Brazilian Copper Association is the only entity that focuses explicitly on copper. It aims to promote production and consumption of copper along the entire value chain, from geological research to smelting. It is also closely linked to several international cooper associations and provides statistics and other information on the copper industry.

In addition to the power of the regulator, which is based on national legislation, Brazil has a complex, layered system of legislation at the state and municipal level to which mining companies must comply. The ANM, for instance, has local offices in each state capital (i.e., 27 local agencies). Also, despite the existence of the IBAMA, most environmental licenses are issued at the state and municipal levels.[16,17]

The size of Brazil prevented this research from covering the 26 states plus the federal district. However, it was possible to identify that, at least in the top three states with a significant mining presence (Pará, Minas Gerais, and Bahia),[18] local institutions play an essential role in supporting mining.

- In Pará, where the mining industry accounts for 80 percent of the state's total exports, reaching US$12.5 billion in 2018 - 16 percent (of the 80%) is copper. Sinmineral (Union of the Mineral Industries of Pará) is the main representative institution for mining. It represents 13 mining companies, including two major copper producers (Sinmineral, 2019).
- In Bahia, CBPM (Bahian Mineral Research Company), a public institution, plays a similar role to Sinmineral.
- In other states and municipalities, it is also usually local state and municipal departments that support the mining sector.
- In Goiás, the Sector Chamber of Mining (CASMIN), which is linked to the Federation of Industry, supports mining companies.
- IBRAM, the foremost institution representing the sector, tends to function as a central hub, integrating local and dispersed initiatives into debates on the development of mining.

Figure 11 illustrates the main government institutions and Figure 12 the main non-governmental institutions related to the mining industry's regulatory framework.

16 Environmental licenses are issued according to the level of environmental impacts that the new venture will cause. If the impact will only be local, the municipal agency will issue licenses. If it goes beyond the limits of the municipality, the state agency is responsible for granting licenses. If it is a large undertaking with broad, territorial impacts, IBAMA is responsible for licensing.

17 Less directly linked to mining but still important for the regulatory environment are Federal public defenders *(ministerio publico* in portuguese) who have offices in each state and oversee the legality of activities in all areas of public life. They defend the public's interests. If mining activities are causing harm or are seen as potentially causing harm these prosecutors can sue the mining firms to find redress to the situation and protect the public interest. The public defenders often participate in public debates related to mining's 'social license'.

18 It is worth mentioning that the Association of Mining Municipalities of Minas Gerais and Brazil, whose main role is to collectively discuss the impacts of mining on municipalities, suggests better uses for royalties and plans economic alternatives for the cities after mine depletion.

Figure 11. Main Government Institutions Related to the Mining Industry's Regulatory Framework

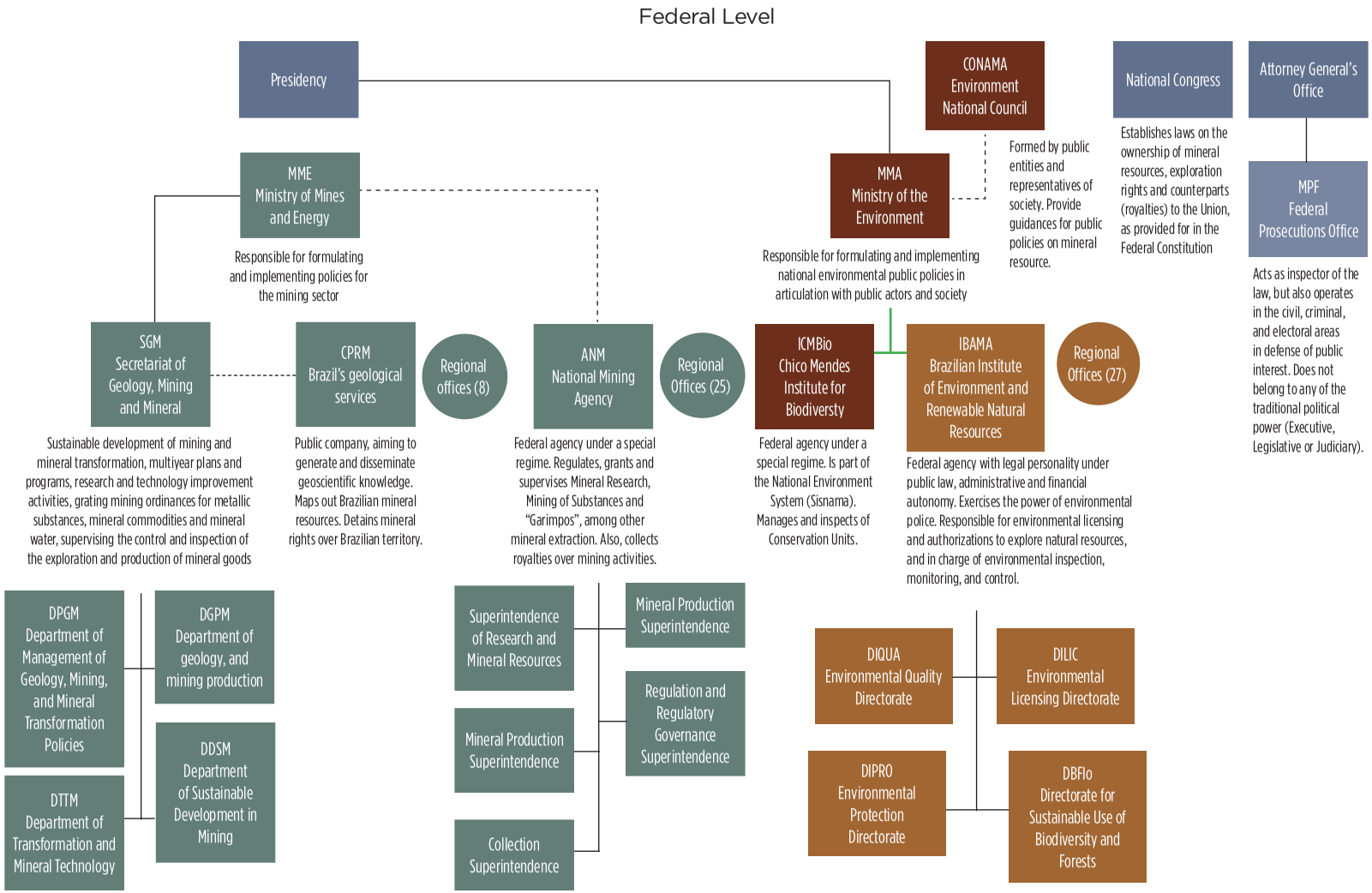
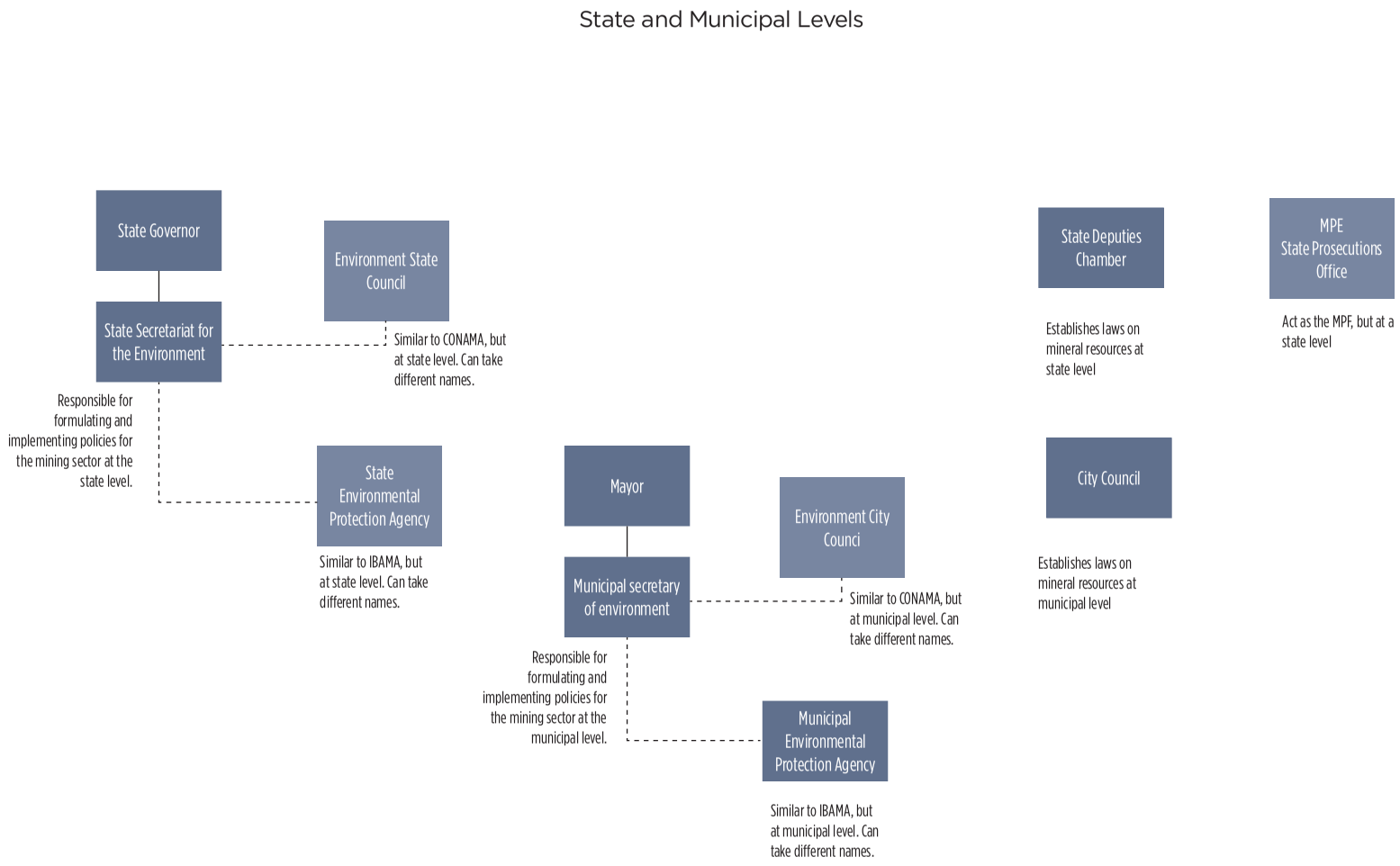
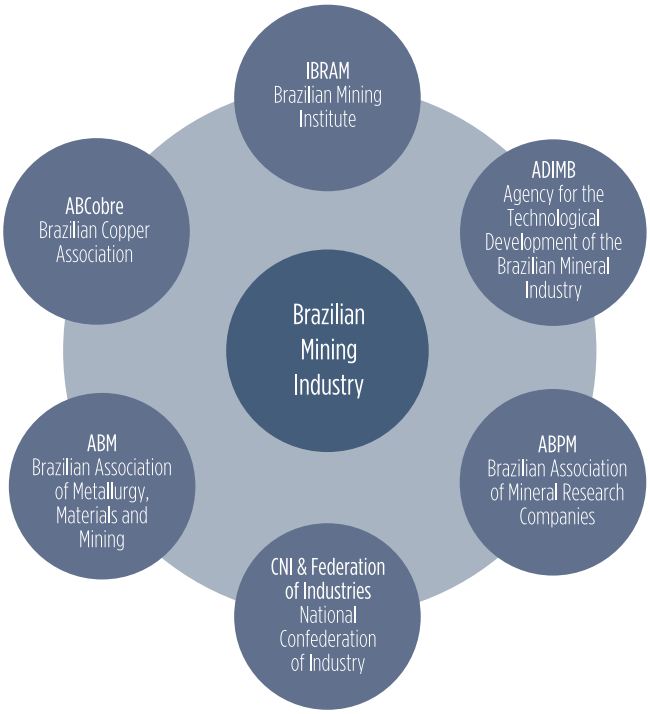


Figure 11. Main Government Institutions Related to the Mining Industry's Regulatory Framework *(continued)*



Source: Authors' elaboration.

Figure 12. Main Non-governmental Institutions Related to the Mining Industry's Regulatory Framework



Name	Mission and Goals	Site	Members
IBRAM	Private, non-profit institution. Represents the interests of companies in the mining sector, fosters innovations, and promotes the dissemination of best practices and technologies.	Brasília and Belo Horizonte	130 members from the mining industry
ADIMB	Private, non-profit business association. Promotes technical and technological development, and training for the mineral industry.	Brasília	MME, IBRAM, ANM, and MCTIC* are natural members; roughly 30 members, including junior mining companies
ABPM	Private, non-profit business association. Promotes and disseminates mineral research and represents the interests of companies that carry out mineral research, such as Juniors.	Rio de Janeiro	33 members, including mining firms and suppliers – for Juniors
CNI	Private, non-profit institution. Represents the interests of industries. Federations are linked nationally to the Confederation of Industries and regionally to the industry unions.	Brasília and all states	Spread over all 26 states and the federal district; in some states, organized through sector chambers; in Minas Gerais and other states, there is a chamber of mining; number of firms varies by state
ABM	Private, non-profit business association. Promotes technical-scientific evolution and innovation in processes, products, and management. Also promotes capacity building. Composed of companies, institutions, universities, and individuals linked to the metallurgy, materials, and mining sectors.	São Paulo	Members: 44 companies (mining firms and suppliers), 1,627 individual members
ABCobre	Private, non-profit business association. Defends, strengthens, and develops the copper value chain, fosters innovation of products and services, and encourages the use and consumption of copper and its alloys, promoting its qualities and forms of application.	São Paulo	10 companies, including some mining suppliers

Source: Authors' elaboration.
*MCTIC: Ministry of Science, Technology, and Innovations

The mining value chain includes a dense network of institutions that support its growth. Often organizations get together to discuss common problems, strengthen their market promotion, organize national business fairs, and represent Brazil in international events on mining.

In early 2019, when this analysis was carried out, there was a feeling of optimism around the possibility of new public policies that could expand mining exploration and create new opportunities for the mining value chain. The first few months of the Bolsonaro presidency brought the replacement of a regulatory government agency with a new independent agency (the ANM) that came with the promise of replacing the old bureaucratic system for licensing with a modern system of regulation. However, the social and ecological tragedies caused by the collapse of Vale's tailings dams first in Mariana (2015) and later in Brumadinho (2019) countered that optimism with a reality check that neither a government-led agency nor an independent one was able to avoid. The ANM had barely started operating when the seriousness of the disasters quickly led to the MME constraining the ANM's actions. Shortly after, the ANM's budget was cut significantly as a result of Brazil's more general economic crisis, which led to an even bigger public criticism of the ANM's role. Thus, despite being dense, the mining network is not as effective as it could be.

An example of this lack of effectiveness was a joint effort made by the Brazilian Industrial Development Association and the Brazilian Association of Metallurgy, Materials, and Mining in 2014, with IBRAM's support, aiming to gather mining suppliers on a single digital platform. The project—Mapping the Supply Chain of Goods and Services of the Mining Industry—comprised five mapping products: (i) a work plan, (ii) a methodology to classify goods and services, (iii) a mapping of the mining companies that operate in the country, (iv) a survey of the supply chain, and (v) a mineral catalogue. The mineral catalogue, inspired by similar projects developed in the oil and gas industry, was never completed even though it was staffed with a team of technicians and supported by the government.

More notably, the difficulties creating an active industrial policy for the mining industry highlight the lack of integration. As pointed out by the leader of a government institution interviewed in the exploratory phase of this study, although Brazil has a long history of different industrial policies, with varying degree of success, a series of new efforts to promote industrial growth took place in 2011. Until then, under the aegis of the *Plano Brasil Maior*, an industrial policy created in 2008, the federal government had already established 19 competitiveness councils, one of which was the mining council. Based on these initiatives, an entire sectoral agenda was built to develop the mining industry. PROMINER, a pro-mining program that was part of that agenda, aimed to map the value chain (as mentioned above), produce a catalog of suppliers, and promote a supplier development program. In addition, the intention was to map the productive and technological gaps in the chain, create a national content policy, and create the so-called Mineral Processing Zone led by the DNPM. Many of these initiatives have evolved, but after the outbreak of a series of political and economic crises, many actions were stopped. Thus, a project of regulatory amendments to provide tax deductions for small investors on the stock exchange has not evolved, interrupted by amendments to the Mining Code. In the words of one of the industrial leaders interviewed for this study:

> "During Dilma's second term, and afterwards during President Temer's term, the country was left without policies. The new federal government did not adopt any industrial policy.

> Then, we started to take more specific actions of what we call productive and technological development and innovation, but without an industrial policy framework."

Apart from obstacles related to Brazil's political landscape, institutions tend to be very focused on their role, one link in the chain, and tend to miss the more systemic point of view. The statement of a mining executive from Imerys S.A. exemplifies this feeling of individualism. In his view, individualism does not help to develop the sector, since the same problems have been faced for years with no effective action to solve them:

> "I've been listening to the same things being debated since 2017: that the sector needs more unity, investments, regulation...about difficulties obtaining permits. What are we going to do with regards to the sector? Everyone is looking after their own business and taking care of it." (Ribeiro and Souza, 2019, p. 71)

Though this study is not specifically about environmental issues, it cannot disregard the importance of Brumadinho's tragedy in changing the institutional landscape. After the disaster, there was rapid coordination between local and federal actors to quickly change regulations to ensure safety and to improve the badly damaged image of the mining sector.

The Minas Gerais government issued new bills forbidding the type of waste management (upstream tailings dams) that was involved in both the Mariana and Brumadinho accidents. On one hand, new regulations further constrained firms, but on the other, the mining sector was pushed to be safer in the future.

Likewise, the state government, the mining chamber, and the Federation of Industries of Minas Gerais reacted swiftly and joined forces with other entities to create awareness of the value added by the mining industry to the livelihoods of local communities. These actions sought to restore and improve the public image of the mining sector and prevent more mine closures, which financially damage the mining companies and reduce the tax income for local governments. The following are other examples of joint actions to reinforce the mining industry:

- At a major sector event, EXPOSIBRAM, IBRAM provided a letter of commitment to society. In this document, the institution committed to operational safety for dams and waste disposal structures, occupational health and safety, mitigation of environmental impacts, local and future development of territories, a better relationship with communities, better communication, diversity and inclusion, innovation, water, energy and better waste management. In its very beginning, the letter states: "We are committed to a profound transformation of the mining industry, in our processes and techniques, in our relationships with people and with nature" (Portal da Mineração, 2019a). As stated by IBRAM's president, "IBRAM, which until recently was seen as a defender of the interests of one or a few large mining companies, changed its way of acting to be, in fact, representative of mining" (Goldberg, 2019).
- At the same event, IBRAM provided a letter of commitment to the international movement Women in Mining. The movement aims to leverage the participation of women in mining, a traditionally male sector. Moreover, IBRAM released an Action Plan for the Advancement of Women in the Industry (IBRAM, 2019c, 2020b).

- Some months later, in partnership with 50 specialists and firms, IBRAM launched Good Management Practices for Dams (Portal da Mineração, 2019b).
- IBRAM and the Regional Council of Engineering and Architecture joined forces to promote an event on new techniques and technologies to improve mineral waste management. The event (in June 2019) was attended by suppliers of new technologies, mining firms, governments, and academics. For the event, 38 companies, national and international, were selected to present solutions to mining waste management (*Mining News*, 2019b).
- The MME, through the SGM, prepared a proposal, PDTec Mineral (Technological Development Program for the Mineral Sector), to improve the use of technologies in mining production. The program would have three axes: support for small-scale mining; research, development, and innovation for minerals and processes that leverage sustainable development; and collaborative R&D projects. The program depended on the implementation of funding (Mining News, 2019c).
- In 2020, the MME announced a digital launch of five services within the scope of the mining sector that aim to bring "greater transparency, simplification, and convenience to citizens and companies interested in the actions of Brazilian mining," a path to reduce bureaucracy (Trindade, 2020). The ANM is going in the same direction, launching digital platforms for mining firms to deal with licensing processes.
- The Association of Municipalities with Mining Activities joined forces with IBRAM to establish a technical cooperation agreement for sustainable mining development. They also asked the federal government to refrain from cutting the ANM's budget (AMIG, n.d.).
- The National Confederation of Industry reactivated its Mining Chamber (Abreu, 2019).
- CPRM presented at Prospectors & Developers Association of Canada's 2019 convention, the world's premier mineral exploration and mining convention. CPRM carried out in Canada maps of favorability "Knowledge-driven" of potential areas of several Brazilian mineral provinces (InMine, 2019).
- ADIMB signed a cooperation agreement with Australian Amira International, a non-profit organization that aims to promote innovation in natural-resource-based industries. Another settlement was established between Amira and CPRM for technical cooperation (Vaz, 2019).

More education is required to build awareness about the necessity to reduce municipalities' dependence on mining. It is important to note that mining generated around US$770 million in income for their host communities in 2018; 43 percent collected in Minas Gerais and 43 percent in Pará (Goldberg, 2019). As discussed at the EXPOSIBRAM event in September 2019, municipalities do not always direct this money toward increasing the quality of life of their populations or to plan for economic conversion after the depletion of mining. Currently, in addition to CFEM (royalties from mining, a portion of which are distributed to municipalities), local communities are supported to some extent by companies that operate in their municipality either by sponsoring local development projects or by ensuring purchases from local suppliers, with companies investing in surrounding communities. However, royalties and company efforts are perceived as insufficient to promote local development. More is expected of local public authorities to better use CFEM.

Innovation Performance

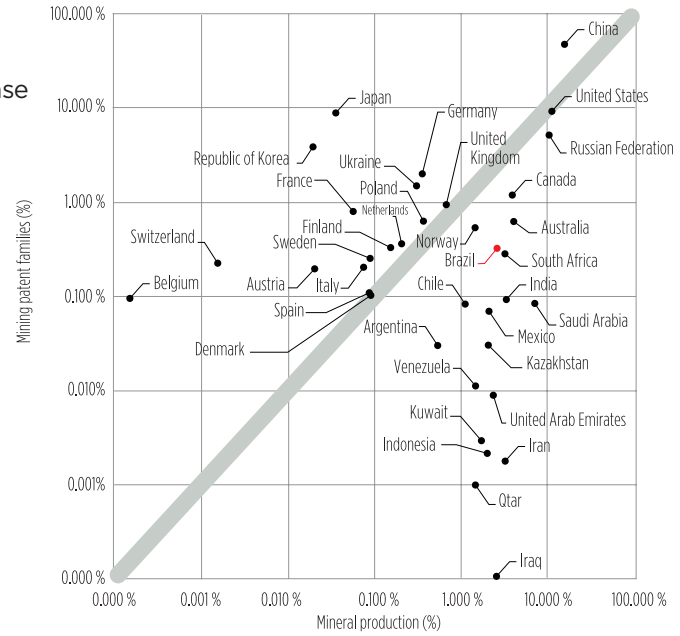
Compared to other countries, Brazil has historically underinvested in innovation support (CNI, 2017). According to MCTIC (2019), in 2017, total spending was approximately R$82 billion (US$25 billion at historical exchange rates), with approximately half coming from public investment. However, after the economic crisis (2014–18), cuts to the public budget affected funds for R&D. For example, R&D investments as a percentage of GDP decreased from 1.34 percent in 2015 to 1.26 percent in 2017. According to MCTIC, while Brazil invests less than 1.3 percent of its GDP in R&D, countries such as France, the United States, and China invest more than 2 percent, with Germany and Japan investing more than 3 percent.

In 2019, the Global Innovation Index ranked Brazil 66th internationally in terms of innovation performance, placing it fifth of the Latin American and Caribbean countries (for comparison: Chile's rank was 51, Argentina's, 72, and Peru's, 86). Between 2011 (ranked 47th) and 2017 (ranked 69th), Brazil's ranking dropped 22 places, though it is worth noting that the methodology and number of countries in the index had changed significantly since 2011 (Cornell University, INSEAD, and WIPO, 2019).

The literature widely recognizes that patents are neither the only nor the best way to assess the level of technological development of companies or countries (OECD, 2015). Still, patents remain a reliable indicator of innovation, as they demonstrate the level of efforts to develop new products and protect them in the market (Pereira and Vasconcelos, 2014).

According to the OECD classification, the mining industry is considered a sector of medium-low technological intensity (Morceiro, 2019). Comparing Brazil's performance with that of other OECD countries suggests that "Brazil is far from the OECD's R&D intensity in most sectors of the economy" (Morceiro, 2019, p.11). However, Figure 13 shows that while Brazil is a relative underperformer in terms of filing mining patents in the WIPO database, it is relatively well positioned compared to other Latin American countries (Daly, Valacchi, and Raffo, 2019).

Figure 13. Relative Position of Brazil within the WIPO Mining Database



Source: Daly, Valacchi, and Raffo (2019).

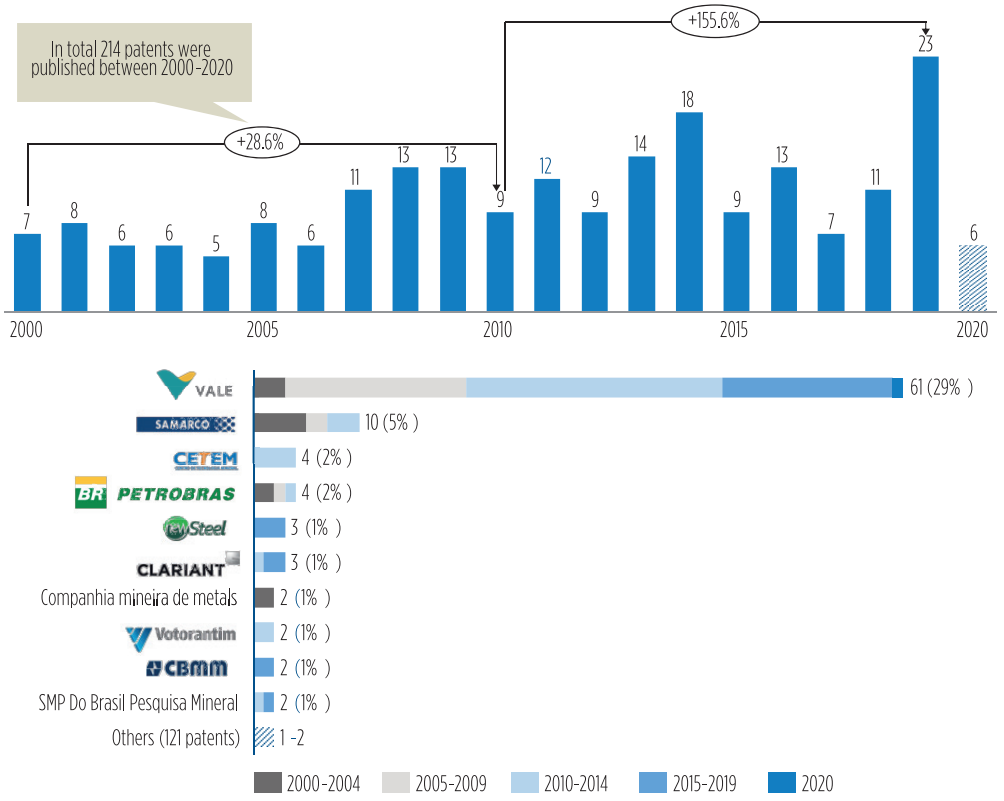
The Activity Dispersion Rate by Sector, confirms the low position of the extractive industry in the innovation ranks: while Brazil's overall index is 34.9, the index for the extractive industry is 17.1.

In 2017, 28,667 Brazilian companies filed a patent application, 7 percent less than in 2016 and 15 percent less than in 2013, the peak of applications since 2000. Of these applications, 70 percent were made by non-residents. As for approved patents, there were 6,250 in 2017, the highest number since 2000. The data are not segmented by sector preventing further analysis (MCTIC, 2019).

Analysis of Brazilian Patents in Mineral Mining Sector, 2000–20

We searched Brazilian mining patents over the previous 20 years based on several broad Cooperative Patent Classification and International Patent Classification codes and combined these with specific keywords in the titles and abstracts (our search excluded oil and gas and non-metal mining). This search identified 214 patents over a 20-year period. The results show a fluctuating number of patent publications per year but with a significant upward trend over the past 10 years (Figure 14).

Figure 14. Patent Publications in the Mineral Mining Sector in Brazil by Date of Publication



Source: Authors' analysis using Patent Inspiration database.

Of the mining companies, Vale registered the most mineral mining patents in Brazil between 2000 and 2020. The company's 61 registered patents accounted for 29 percent of all mineral mining patents during the period. The second most active company was Samarco, which filed 10 patents in the same period (note that Samarco is a subsidiary of Vale, further reinforcing Vale's dominance). In Brazil, Vale also registered the most patents in all sectors from 2010 to 2017, with a total of 132. The company is ranked fourth in terms of number of patents across industries in Brazil (Mining News, 2018a). According to its website, Vale holds more than 1,000 patents worldwide, highlighting the huge investments Vale has made in innovation. The company's technological institute has two locations, one in Pará and the other in Minas Gerais, and collaborates with many Brazilian universities (Daly et al., 2019). Vale invests heavily in digital transformation, a program based on four pillars: analysis, integrated systems and chains, robotics, and autonomous equipment. The company has stated that, among other technological innovations, it already uses the internet of things, advanced analytics, machine learning, artificial intelligence, and mobile applications. In 2018, Vale created a digital laboratory in Rio de Janeiro and, in January 2019, the company opened its Center for Artificial Intelligence in Vitória in Espírito Santo state. Other mining firms and international suppliers are following this trend, though from a lower starting position. For example, Nexa is strongly investing in automation. Some examples of innovations are electronic identification of movement of people, machinery, and equipment; production management in real time; remote mine operation (using data, voice, and image transmission); and digital reading of mining and loading operational cycles.

While this report was being written, Jaguar Mining (gold mining) announced that it would install a low-cost anti-collision system in its underground operations, a project that was developed within the mining hub. The project aims to reduce costs and increase safety in operations (*Mining News*, 2020). On the supplier side, in 2018, AABB (one of the largest suppliers, also an integrator) announced that it would invest R$1 million (about US$250,000) in a robotics training center in São Paulo (*Mining News*, 2018b).

This type of large investment requires resources that many small- and medium-sized companies do not have, therefore they either invest in innovation at a slow pace on their own or they partner with other companies, technological institutes, or universities.

In any case, not all innovations are registered as patents. As stated by a former Vale employee (currently an innovation manager at a non-profit institution) interviewed for this study:

> Software can be registered, patents can be registered, but not all will evolve into formal patents at [the National Institute of Industrial Property]. (...) Coca-Cola says its formula is an industrial secret that is over 100 years old. Coca-Cola's formula will never be put on a patent, as people will look and know how it is made. Within a certain period, it would become public domain.
>
> What needs to be addressed in developing an innovation partnership is who can use it, when, for how long, and why. Many agreements establish that, in the end, both can use the innovation, and nothing is attributable to anyone, usually with shared 50:50 investment. In the (rare) case of generating a patent, so that one party can sell it, the other needs to authorize patenting and sales and royalties are negotiated. But what would a mining company do with a patent outside its core business? For example, it may want to improve the

ball mill, but a mining company is not going to manufacture ball mills. So, it would prefer to work in a partnership.

Apart from this, certainly, the time needed for a patent to be analyzed and issued in Brazil is a barrier as it takes significantly longer than most countries. Thus, it is not surprising that most (70 percent) of the interviewed firms did not have any patents or brands registered. The ones that did tended to be the most technologically oriented companies, such as lab equipment producers, software producers, or engineering firms producing high-tech mining processing machinery and equipment.

Institutional Support for Innovation

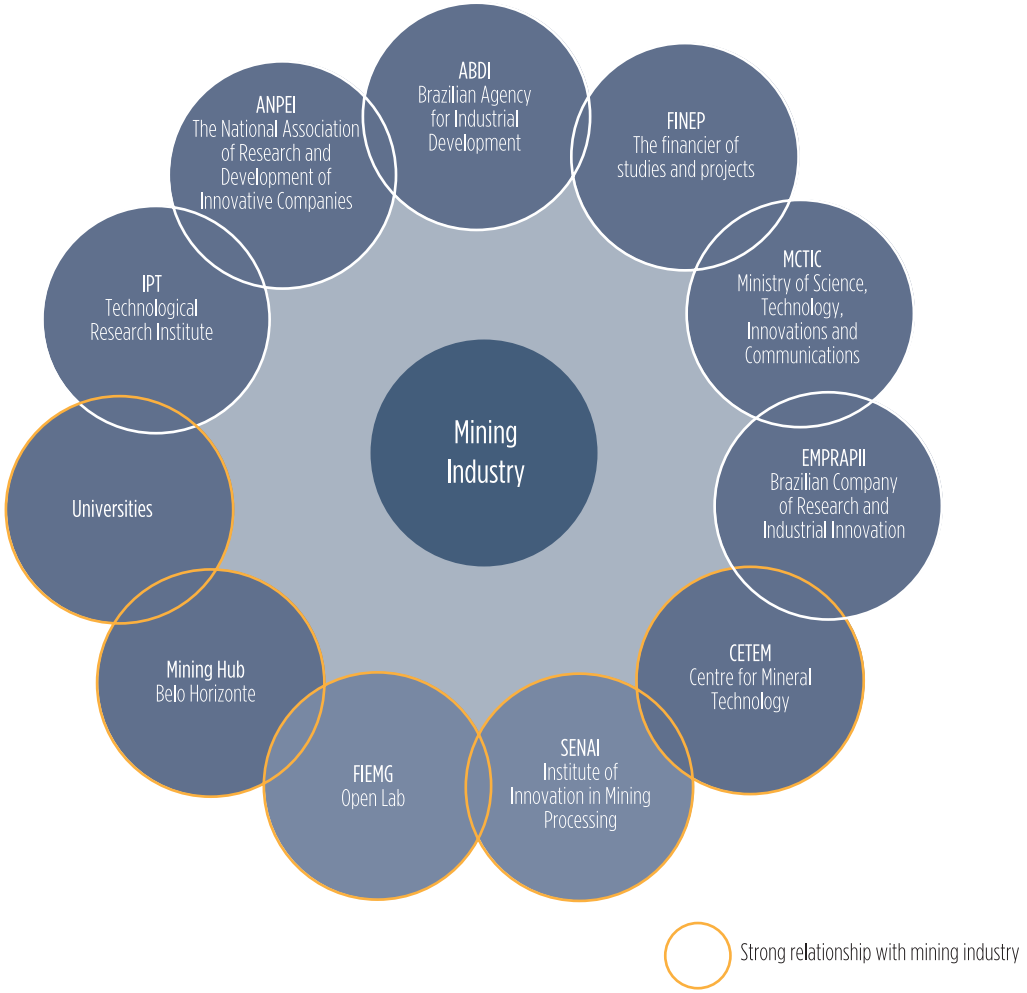
Brazilian National Mining Innovation System

Regarding systems of innovation, there is a large network of research and formal training made up of universities and technical and technological institutes located in different parts of the country. Many were considered by interviewees to be centers of excellence in their areas of expertise, including mining engineering at the Federal University of Minas Gerais, the SENAI Institute of Innovation and Mineral Processing, and CETEM (the Center for Mineral Technology). While the first two entities are located in Minas Gerais, Brazil's specialized mining cluster, CETEM is in Rio de Janeiro. These entities have carried out much of the applied research, helping firms and universities collaborate (a challenge in Brazil, where academia tends to have tenuous links to firms and undervalue applied research) and pushing for more innovation in the sector. Also, Brazil's Geological Services (linked to SGM) offers the main basis for mapping the Brazilian territory regarding main copper and other mineral reserves.

For instance, "CETEM engaged in-house R&D in metallic copper, which was soon demanded by local firms. Together with Mineração Caraíba, CETEM sought to pioneer the development of a hydrometallurgical process in Brazil. To this end, in-house research efforts were combined with technical visits—or doing, using, and interacting—to several copper-producing centers, such as Chile and Peru. These learning efforts paid off, as Brazilian firms achieved exceptional copper recovery values—even higher than those practiced in other traditional copper-producing countries" (Branquinho, 2014, cited by Figuereido and Piana, 2020, n.p.).

Funds for innovation are available through a range of institutions that support R&D, most of them linked to public institutions. An interesting exception is the National Association of Research and Development of Innovative Companies, a private independent association of firms, with 60 percent of private investment funds earmarked for innovation. Figure 15 is a diagram of the main organizations in Brazil's innovation system and Appendix 8 provides further details about institutions linked to innovation.

Figure 15. Main Organizations in Brazil's Innovation System



Source: Authors' elaboration.

Since data on innovation in mining is scarce, this study is particularly relevant. As noted by Pamplona and Penha (2019), the concept of a Brazilian innovation policy is quite recent since, up to the 2000s, policies for innovation tended to be closely interlinked with industrial policies. The Technological Innovation Law and *"Lei do Bem"* were milestones toward a more structured regulatory framework exclusively for innovation. The first (Bill 10,973 of December 2004) was created primarily to stimulate partnerships between academic institutions and Brazil's productive sectors. The latter, Law 11,196 of November 2005, establishes tax incentives for legal entities that carry out R&D for technological innovation.

Currently, Brazilian innovation policy is set out in the National Strategy for Science, Technology, and Innovation, coordinated by MCTIC. The strategy, which was built by focusing the innovation agenda according to economic sectors, prioritized the mining industry. Two other initiatives complemented the strategy:

- The National Mining Plan–2030 (PNM2030), coordinated by the MME, aimed to strengthen public governance, adding value, fostering knowledge, and enhancing the sustainability of the mining industry. Note: On July 10, 2020, the minister announced that there would be an update by August 2020 with clearly defined goals up to 2023 (Brandão, 2020).
- The Inova Mineral plan, jointly launched by the Brazilian Development Bank (BNDES from the Portuguese) and the Funding Authority for Studies and Projects (FINEP from the Portuguese) in 2016, focuses on funding technological developments within the mining value chain.

However, most of these policies and the support measures discussed above focus on what are considered strategic minerals for the future, like cobalt, graphite, vanadium, and niobium. Inova Mineral also supports R&D of technologies and products focused on minerals with a high commercial deficit, such as those for producing fertilizers. Copper is considered for support (or at least not excluded) from other lines of financing to improve and scale mining technologies (mineral processing technologies and processes to reduce and mitigate environmental risks and impacts) and pioneer development and production of machines, equipment, software, and systems for mining and mineral transformation that can be more efficient and less harmful to the environment (BNDES s.d., Mesquita, Carvalho, and Ogando, 2017). According to the BNDES website, between launch in 2016 and the end of 2018, the proposed R&D projects of 45 companies (including mining suppliers) were accepted for funding from Inova Mineral.

A particularly interesting finding was a partnership between FINEP and the Inter-American Development Bank (IDB) to promote Inova Mineral. According to news published in the local press, the IDB would finance the first installment of US$600 million (FINEP would provide the additional US$103.6 million) for the Innovate to Grow program. This first installment would be part of a larger credit line, totaling US$1.5 billion in conditional credit for investment projects aimed at promoting the productivity of Brazilian companies through more private investments in innovation. According to FINEP, these resources would be made available to companies from different sectors, including a public funding entity like Inova Mineral (IDB, 2018).

Despite institutions and resources available to support innovation, more than half of the firms we interviewed reported ignoring any political actions or government programs.

A PINTEC report on innovation highlights that, in a universe of around 117,000 Brazilian companies with 10 or more workers, only 34 percent have innovated in product or process. Although this figure lacks precision as it encompasses mining and oil and gas, it provides a basis to evaluate the potential to increase R&D in the mining value chain. For the extractive industry, the index is currently at 15 percent compared to 42 percent three years ago. Interviewed firms noted innovations in the following areas: reducing their environmental impact and/or improving health and safety (87 percent), improving the quality of their products (85 percent), maintaining their current market share (82 percent), increasing productive capacity (83 percent), and increasing production flexibility (82 percent). Innovations with less impact were associated with, for example, creating new products or opening new markets. Market growth and cost reductions were not among the main listed results from innovation (IBGE, 2017).

With regards to testing, Brazil is in a good position. There are plenty of local facilities and capabilities for testing in mining. Large mining firms have in-house labs to do their own tests. SENAI plays a role on

providing tests and receiving samples and has mini-plants on its premises in Belo Horizonte in Minas Gerais and other mining states that are used by medium-sized firms. CETEM (based in Rio de Janeiro) also provides lab services and advanced testing to large and medium firms all over the country.

There are two broad categories of testing required. First, daily tests for, for example, granulometries and grading samples. Second, tests to certify the quality of material to be exported (either at the project stage, when a company is looking for funding, or later during regular export operations). Still, for exporting, regardless of the high testing capabilities in Brazil, tests need to be done locally and abroad. Potential funders still prefer to see corroboration of the tests from third-party labs abroad (based on interviews with the ANM and the ABPM). It is a matter of trust, not capabilities.

SGS Geosol (with laboratories in the mining states of Goiás and Minas Gerais) is a leading Brazilian firm providing tests and lab equipment to the mining sector. There are two suppliers in Minas Gerais that supply items for laboratories and they were both interviewed for this study.

The mining sector also benefits from many magazines and newspapers that monitor market trends and provide structured information to the mining sector through their websites.

Mining Hub: Supporting Innovation

The relatively recently established (January 2019) Mining Hub in Belo Horizonte, Minas Gerais, is a striking innovation initiative. Belo Horizonte was already known for innovation based on start-ups since the region has around 320 of them. In 2013, the first accelerators were set up, encouraged by SEED, a state program to foster accelerators. One of those accelerators, Techmall, financed by a fund that supports innovative firms, joined a project to create an open innovation hub for the mining sector. Techmall joined the project using the name of a spin-off from Techmall called Neoventure. The project was first conceived by Ferrous, a medium-sized mining firm focused on iron extraction (later bought by Vale) that, based on previous knowledge of open innovation initiatives, was looking for partners to innovate. In a short period, the project evolved to include five mining firms that matched around 20 start-ups being accelerated by Techmall. In a second phase, the project was presented to IBRAM, which engaged in the initiative and soon thereafter 22 mining firms were part of the Mining Hub. In 2020, the Mining Hub encompassed a total of 23 mining firms, 21 mining suppliers, and about 20 start-ups. Resources to develop projects come from associated firms and IBRAM. In its first year, the Mining Hub's activities had a 25 percent success rate, which IBRAM considers high compared to similar initiatives around the world. This result reflects the hiring of start-ups after two cycles of project acceleration (the Hub is in the phase of the third cycle now) (Portal da Mineração, 2020). In the first 18 months, the Mining Hub received 690 project registrations from start-ups, of which 190 were screened by the technical team to participate in a proof of concept process, with 16 chosen and four start-ups hired (25 percent). For the proofs of concept, proponents present a practical model to prove the (theoretical) concept established in their projects. IBRAM's official website states,

> "the topics of dam safety and management of mineral tailings deserved special mention in the first year of the Mining Hub, with the direct involvement of several mining companies

that invest attention and resources in these themes, such as Nexa, Vale, ArcelorMittal, Vale, Samarco, Usiminas, CSN, and Kinross, among others. Some projects have evolved actions to monitor dams and use waste in civil construction, for example. For 2020, the Mining Hub will devote special attention to achieving greater reach with science institutions, such as universities and research institutes" (Portal da Mineração, 2020, n.p.).

In 2020, the Mining Hub's primary areas for R&D included operational efficiency, alternative energy sources, water management, waste and waste management, operational health and safety, and social development (IBRAM, 2020c).

For its originality, the Mining Hub has been visited several times by organizations inside and outside Brazil (more than 1,000 people in the first year). It has evolved to incorporate new lines of innovation, including social impact and diversity. According to most interviews, what is novel about the Mining Hub is the concept of shared knowledge, as a solution developed by one firm can be used by others on the basis of the work developed in the Hub.

Although the main focus of the Mining Hub is to develop collective solutions, a new line of research has been created to enable a firm to launch a competition to get ideas to resolve its own internal challenges. However, intellectual property rights remain under the control of start-ups. For example, Vale recently announced (June 2020) the launch of M-Spot Cycle 1 with an investment of more than R$2.25 million (approximately US$410,000). The goal is to find innovative solutions to 15 challenges in seven areas: energy, railways, geotechnics, technical marketing, navigation, pelletizing, and ports (Soares, 2019).

In addition to the Mining Hub, similar initiatives were developed in the Minas Gerais mining cluster. FIEMG launched FIEMGLab on the premises of the SENAI Center for Innovation and Technology. Nexa Resources is already in the third edition of its open innovation program, created in 2016, called the Mining Lab Challenge. Another initiative by the same company is the Automation and Information Master Plan, a 10-year plan to implement new technologies to optimize operational processes and ensure accurate information to improve its main indicators. However, this does not prevent the company from joining the Mining Hub.

Despite evidence of interest in innovation initiatives taking place locally and their promising results, these initiatives remain at a very early stage of development. Apart from some specific cases involving large companies such as Vale, until recently, innovation has not been a hot topic among local institutions and mining firms. However, following the Vale accidents, the priority of ensuring dam safety is shaping the innovation landscape and providing regulatory incentives to come up with solutions. Indeed, according to the Mining Hub, after Brumadinho, more mining firms engaged with the Hub, almost doubling the number of participants.

There is consensus that the mining sector is going through a major uptake of new technologies, mainly focused on digital transformation. Examples of projects being developed or applied in Brazilian mines include

- digital twins (a simulated environment to test production hypotheses and operations) used to assess the exploitation potential of mineral deposits by comparing them with similar types,
- 3D mapping and modeling software for use in geotechnical maps (already in use at Anglo Ashanti),

- artificial intelligence (AI) and algorithms applied to mineral research and defining investments (in use at Nexa),
- R&D to develop electric vehicles to reduce greenhouse gases,
- virtual reality and simulations for HR training on mining operations, and
- digital control centers to capture and analyze information provided by sensors.

Most of these innovations are driven by safety considerations to prevent and avoid accidents, finding new approaches to dry dams and save energy (particularly fuels).

- Vale already has 13 autonomous vehicles controlled by AI, GPS, and radars (speed cameras). By 2023, the company intends to invest US$467 million in Industry 4.0 projects. It inaugurated an AI center in Vitória, Espírito Santo, the Global Center for Artificial Intelligence, in early 2019, with 15 employees and 50 professional partners. According to a local Vale manager, the center aims to capture global data to feed into computational models and algorithms.
- Mineracao Paragominas announced investments of US$1.5 million in fatigue and anti-collision systems for its truck fleet. As stated by a manager from ABB, a major supply firm, "In the past few years, mining companies have immersed themselves in digitalization. And the changes in the sector are happening fast (...) The pressure to reduce costs and increase operational security is great" (Tiago, 2019, p. 57, translated).

Conclusions

Our analysis of the mining institutional framework reveals a strong economic sector that can count on a dynamic and active network of sectoral, governmental, and technical support institutions, some of which are willing to cooperate with each other. However, the mining sector still lacks a more functional organizational arrangement that could better foster its development. The organizations that make up the mining institutional framework have been described in some cases as having overlapping competencies and lacking coordination to create a practical development agenda. Promising projects have not materialized, such as the attempts to map out the value chain and create a common database of supply firms for business purposes. What is even more serious is that the institutional framework was not enough to prevent enormous environmental and humanitarian disasters like the ones in Minas Gerais. As a result, the sector has had to struggle against big losses caused by regulator blockages of mining operations while being burdened by a negative public image.

As for innovation policy, the scenario is similar. Although there are alternatives for firms to get support for innovation as well as policies, initiatives, and funding sources, they lack volume and coordination and often overlap or are discontinued. In such an environment, it is hard for firms to feel confident about the continuity of those policies, a finding confirmed in other studies like the one from Pamplona and Penha (2019) who described innovation policies in the Brazilian mining sector as "ephemeral, uncertain, linked only to the government, poorly structured" (p. 971).

To summarize, the mining industry has a dense institutional support network focused on developing the right conditions for the industry to flourish. However, the institutional climate and the

economic situation show signs of high instability, compounded by the change in government, which has also resulted in staff changes in key positions in several organizations. The change in government delayed some initiatives and completely changed priorities in other cases. In addition, the economic crisis still affecting Brazil has curtailed access to resources, which has meant that the full potential of certain opportunities (including innovation) has not been realized. Innovation tends to happen thanks to individual firm's efforts rather than public policies or collective collaborations. The Brumadinho tragedy might have been a turning point for the mining industry in Brazil and possibly worldwide. Since then there has been and increase in collaboration between local and federal actors to quickly change regulations to assure safety and to improve the sector's negative image. Whether these new collaborations around safety will evolve toward better support for a more innovative value chain is still to be seen.

The Copper Value Chain Map in Brazil

Developing Mining Value Chain Maps

Several integrators helped complete the map as part of the research process for this study. Most of these integrators are foreign companies, as their role is largely self-financed until the end of a project, when the mining company (the client) will pay. Self-financing represents a huge entry barrier for local companies to become integrators, but this study included at least two of the surviving domestic integrators in our sample and they are among the most innovative in the chain.

Other important actors are the junior mining companies. They research and prepare potential mining projects that can then be sold to larger mining companies. If they manage to secure financing, they may carry out the project themselves (which is less common). This study's sample included one junior company, owned by the president of the association that represents smaller mining enterprises.

Traders were not included in the sample since our analysis ended with production of the copper concentrate; however, in a future study it would be interesting to interview the trading link of the copper value chain. Traders buy concentrated copper and sell it on national and international markets. Most large mining companies trade their product without intermediaries, but others sell their production to large traders, such as Glencore. Prices are determined by the London Metal Exchange.

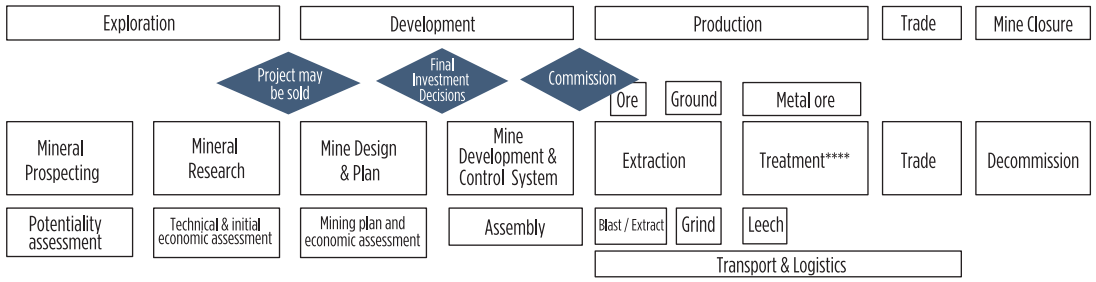
There is no official (government) organization that purchases the production of smaller producers, like there is in Chile, which is already a point for policy discussion for the mining sector in Brazil. Most interviewees did not think that it was necessary for the industry; mining in Chile is much more important for national GDP than in Brazil.

Copper Value Chain Map

Figure 16 shows the value chain map for copper mining in Brazil that was developed and used for this study. Here it is presented as a linear process, but the first stages (exploration and development) could happen several times in a loop before a mine is finally built. The project could also ex-

change hands several times going from a junior to a major mining company until it is either archived as unfeasible or not economically viable or when it receives the go ahead to start construction. It is not uncommon for a project to take 20 years from exploration to start of construction.

Figure 16. Brazilian Copper Value Chain



• Mineral resource identification based on previous public information, including country's geological map issued by CPRM • Geophysical and geochemical analysis • Research project elaboration • Research requirement • Permit*	• Mineral characterization using dip geophysical and geochemical analysis, as well as topographic and geological mapping, lab tests, and drilling targets • May or may not involve open roads and other logistics, as well as camping services, food, and transportation • Drilling and sample certification and testimonies • Final research report • Report approval**	• Technological characterization (basic projects for extraction, treatment, and logistics) • Defining process routes • Mineral samples, lab tests, pilot plants to test concentration methods, energy needed, and related issues • Assessing overall cost of production • Viability analysis • Economic development plan • Mining and extraction requirements • Environmental license requirement • Mining ordinance***	• Mining construction • Open roads • Open pits • Tailings dam construction • Acquisition or leasing of extraction machinery (off-road trucks, cranes, drill rigs, trucks, excavators) • Acquisition or leasing of treatment machinery (mills, conveyor belts, flotation tanks and cells, filters, cyclones) • Logistics and transportation systems • Information to the ANM regarding mining starting point	• Drilling • Blasting • Excavation • Milling and grinding • Separation • Waste disposal and treatment • Monitoring of tailings dams and other critical processes	• Primary and secondary crushing • Primary and secondary screening • Grinding • Flotation and regrinding • Tailings separation • Thickening and filtering • Final concentration	• Domestic market: direct sales • International market: sales to smelters, which will blend the copper for its own use or resell to final users (refiners) • Sales can also be made to traders (intermediaries)	• Remediation of the tailings dam • Recovery of degraded areas • Other required remedial works

Source: Authors' elaboration.
* Can take up to two years to get a permit, which is then valid for another two years.
** Can take up to two years to get approval and could take a year to present the mining plan.
*** Could take five years to receive the mining ordinance.
*** Mainly for copper sulfides; leaching is a different process.
****This is mainly for copper sulphides. Leaching is a different process.

5. ANALYSIS OF SUPPLIER QUESTIONNAIRE RESULTS

Questionnaire Responses

Twenty-eight firms participated in the full questionnaire and interviews. The sample provides data for all stages of the value chain, although it does not represent all suppliers and mining firms in Brazil, as explained in Section 1. There is relative concentration of machinery and equipment and these are most active in the production stage (one firm stands out as providing services along the value chain because it specializes in laboratory equipment). Environmental engineering firms focus on mineral analysis and economic assessment, where obtaining permits is critical. Drilling and sampling firms operate in the early phases of the value chain, while IT and automation engineering firms operate in the mine design and plan, development, and control systems as well as the extraction phases of the value chain.

We plotted respondents against the copper value chain maps based on an analysis of their self-reported category (color coded for ease of reference) and the range of services they provide to different parts of the value chain. Figure 17 presents the positions of firms generally in the value chain, showing that the sample covers most of the chain except for trading and decommissioning (not within the scope of fieldwork) where there is relatively low representation. Table 7 provides a simplified mapping of company activities within the copper value chain.

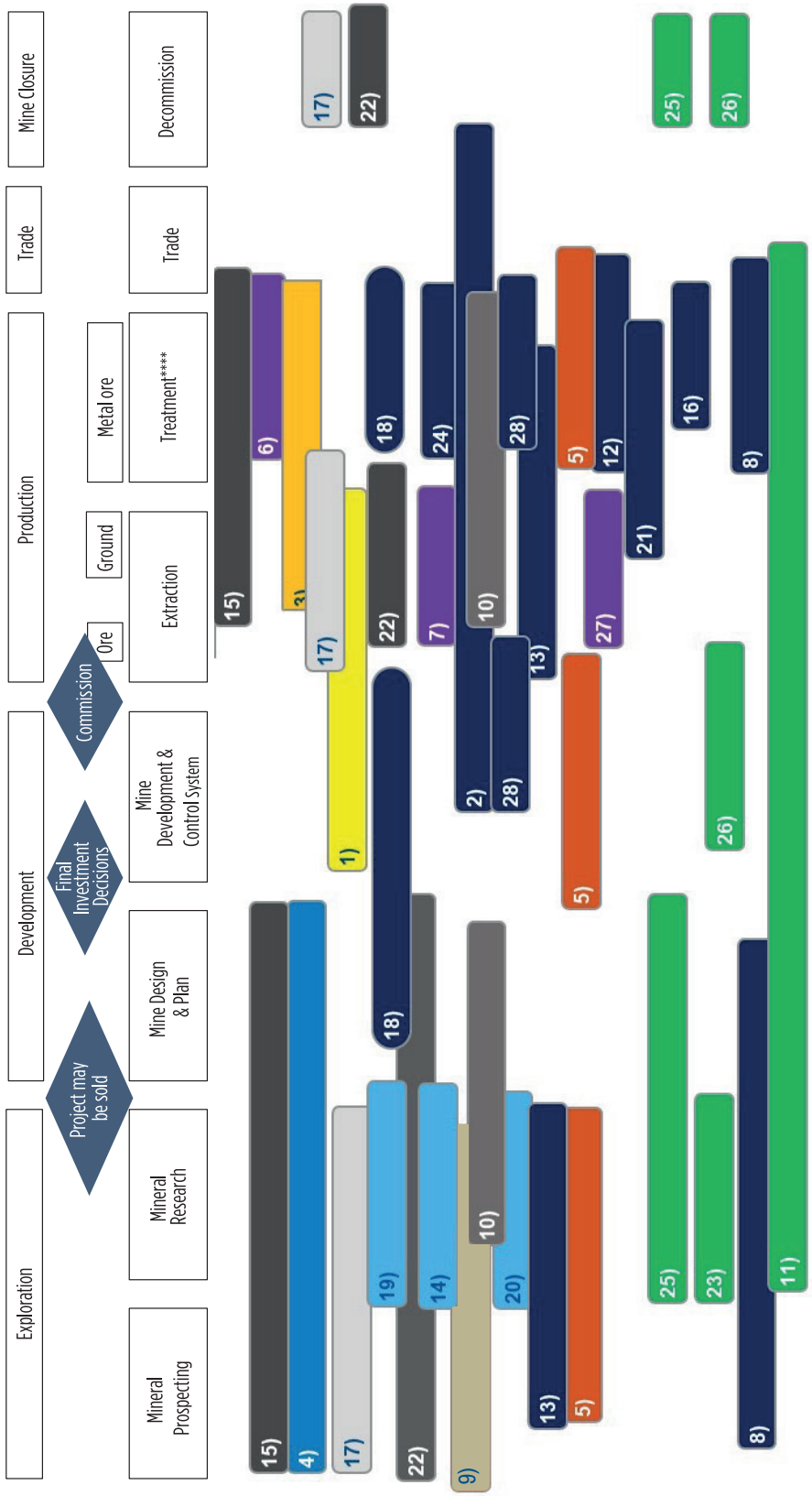
Table 7. Simplified Mapping of Company Activities within the Copper Value Chain

		Exploration		Development		Production		Trade	Abandon
Self-Reported Category (n=28)	Firm ID	Mineral Prospecting	Mineral Analysis & Economic Assessment	Design & Plan Mines	Mine Development & Control System	Extraction	Treatment	Trade	Decommission
Mineral Analysis (laboratories) in Geological Research	5		1		1		1		
Mineral Processing (consultancy)	10		1	1		1	1		
Environmental Engineering	11		1	1	1	1	1		
	26				1				1
	23		1						
	25		1	1					1
Process Engineering	3					1	1		
Engineering and Construction	1				1	1			
Engineering (geology and environmental)	**9**	1	1						
Machinery and Equipment	**8**	1	1	1			1		
	12						1		
	2				1	1	1	1	
	13	1	1			1	1		
	18			1	1		1		
	28				1		1		
	21					1	1		
	24						1		
	16						1		
Drilling and Sampling	14		1						
	19		1						
	20		1						
Geology and Mineral Research	**15**	1	1	1					
	22	1	1	1		1			1
Geological Services	**4**	1	1	1					
IT and Automation	6						1		
	27					1			
	7					1			
Mineral Analysis (laboratories) in Geological Research	17	1	1			1			1
		7	**15**	**8**	**7**	**11**	**14**	**1**	**4**

Source: Authors' elaboration.

Note: The total exceeds 28 because firms are frequently active in multiple categories. Firms in this sample were classified according to the area where the firm operates. Firms that work just on environmental engineering (4) work only in that field. Firms that work on engineering more broadly (9) have two sub-fields: geology and environmental engineering.

Figure 17. Respondents' Activities Mapped onto Copper Value Chain

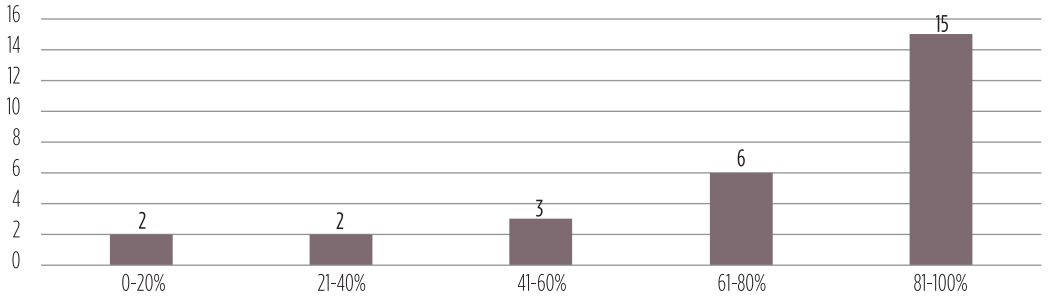


Source: Authors' elaboration. Colour coding is as per Table 7 on page 52.

Revenue from the Mining Sector

Most respondents were primarily engaged in the mining sector, with over half reporting that more than 80 percent of their revenue originated from mining. Since most of our sample was drawn from the specialized mining cluster in Belo Horizonte, this result is not surprising; however, there were some suppliers in construction engineering that were less focused on the mining sector. While companies in equipment and machinery were predominantly heavily focused on mining, one of the respondents, which makes scales for all types of industries, serves a range of different sectors, with only 3 percent of its revenue from mining. Figure 18 shows the number of respondents with various levels of revenue from the mining sector and Table 8 shows the average revenue from the mining sector by category.

Figure 18. Respondent's Revenue from Mining Sector



Source: Authors' elaboration.

Table 8. Average Revenue from Mining Sector by Category (%)

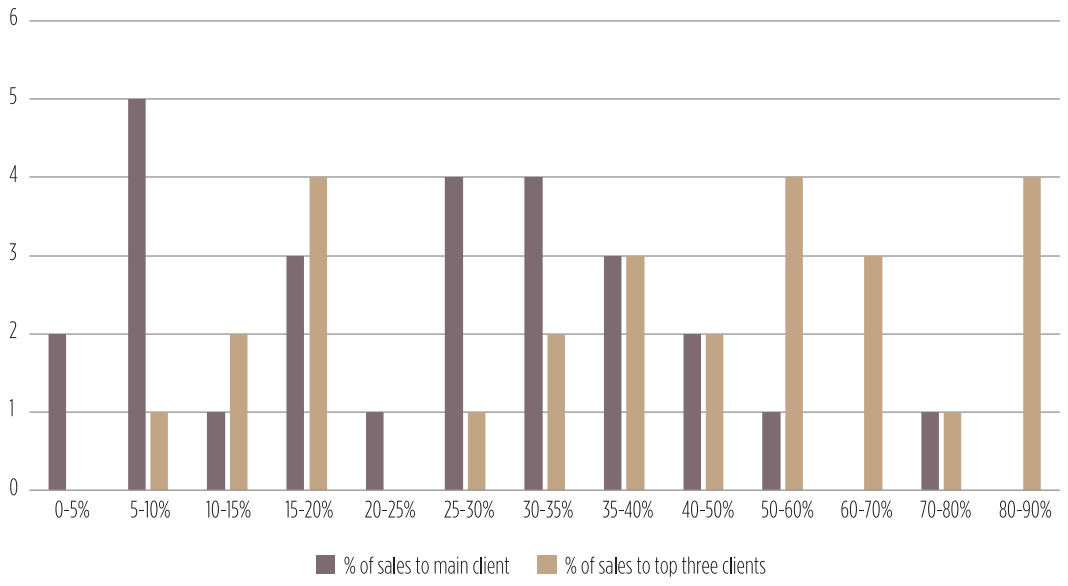
	Average	Max	Min
Mineral Analysis (laboratories) in Geological Research	**90**		
Mineral Processing (consultancy)	**70**		
Environmental Engineering	**75**	100	40
Process Engineering	**100**		
Engineering and Construction	**20**		
Engineering (geology and environmental)	**95**		
Machinery and Equipment	**71**	100	3
Drilling and Sampling	**100**		
Geology and Mineral Research	**78**	80	75
Geological Services	**85**		
IT and Automation	**73**	100	60
Topography	**90**		
Overall Average	**77**		

Source: Authors' elaboration.

Position in the Value Chain

Respondents indicated that they served between three and 30 different clients. In terms of the percentage of sales to their main client or top three clients, most responding companies are not in typical captive (quasi-hierarchical) value chains (Figure 19). Half of the respondents noted that sales to the principal client were below 25 percent of revenue and the median for sales to the top three clients was 40 percent. Only two of the respondents said that over 50 percent of their company's revenue was from their main client.

Figure 19. Respondents' Dependence on Main Client(s) for Revenue



Source: Authors' elaboration.

In addition to the value chain governance to which respondents are exposed, we interpret this finding to show that a significant number of our respondents were not Tier 1 suppliers (at the top of the value chain) where the main suppliers tend to be of foreign origin. Most domestic suppliers are unknown to the leadership of the mining companies and even to the purchase manager, to whom they are often just a number in the supplier register if they are small or providing generic equipment. However, our sample is biased toward innovative suppliers and thus the companies tend to be better known to their clients.

In terms of general awareness of their position in the value chain, all of the respondents recognized their company's relative position and could name competitors. Interestingly, of the 28 respondents

- 24 had national competitors
- 10 had international competitors, which was particularly marked in the machinery and equipment sector where 7 of 9 firms identified international competitors

- 9 reported having nationalized companies (abrasileiradas) as competitors, which was particularly marked in IT and automation where all 3 firms identified a nationalized company as a competitor
- 1 had no effective competitors and operated as a monopsony in its niche

Relationship with Clients and Value Chain Governance

All of the respondents were included in the procurement registry of their major mining clients. This inclusion deserves mention because most suppliers we spoke with noted how difficult it was to finally make the cut and be included in the registry. Even after providing ad-hoc services, a supplier may not be considered for inclusion in the registry. Being included in the registry is by no means a guarantee of regular orders as some suppliers also revealed that even after inclusion they may not hear from a client again, but it is a major hurdle to overcome. In our interviews with large mining firms, where we analyzed the issue of inclusion in the registry from the point of view of the client, it was clear that registries were often incredibly inflated with the contact details of suppliers that were no longer being used and/or had been used on a couple of occasions and then replaced by another supplier. Only three of the respondents in our sample had any type of exclusivity contracts with their main clients, even though our sample was purposefully biased toward innovative firms. From the perspective of value chain governance, these 28 suppliers are not in a captive network with their clients. Instead, arm's length market relations (and sometimes network, albeit often temporarily) seem more prevalent for the suppliers included in this sample, which indicates that even firms that are relatively innovative are still somewhat distant from their clients. This distance might not be conducive to joint solutions or for suppliers to have repeated opportunities to develop more innovative projects with lead firms in the mining industry.

Of course, the reality is more complex. In this study's small sample of innovative suppliers, relationships varied a lot depending on

- the size of the client (not all mining firms equal Vale in power),
- how dependent a client was on the expertise of a supplier (even large mining firms, in emergencies, may need to depend on a supplier),
- the length (long or short term) of the relationship between a client and supplier,
- any previous personal relationship between a client and a supplier (many suppliers previously worked in mining firms).

Access to a mine could be a sign of a close relationship between a mining firm and supplier. However, access may be allowed because it is part of the supplied service and that does not mean a supplier is free to walk around the mine at will.

A sampled firm from Parauapebas provided a clear example of captive governance. The respondent stated that their firm was expanding to fulfill demand from a large mining company and that representatives of the client visited regularly to check on the expansion. But some suppliers refuse to work for large firms, choosing to work with small and medium mining companies with which the relationship is more balanced (this was the case for three suppliers in our sample).

Although many suppliers in the sample have to open their price sheets for scrutiny, they set prices for their clients, which indicates the relative power their reputation for being innovative provides. Well-established suppliers (e.g., consultancies) do not always have to show price sheets and, if they do, they do not necessarily have to negotiate prices. In some cases, particularly when public bidding is required, prices are a major issue and procurement rules can be quite demanding in terms of prices and safety. Mining firms tend to work with centralized procurement as a way of decreasing costs, which leaves small suppliers out of the process since they cannot distribute worldwide. Fortunately, this is not the case for all contracts. Some require joint development of a solution and thus are good entry points for smaller innovative suppliers.

In our fieldwork, the topic of the types of contracts mining companies offer was a delicate subject with suppliers. Several interviewees described contracts as an unavoidable risk for the suppliers, meaning that they accepted the terms because otherwise they would not make the sale. This indicates a power imbalance that hinders innovation because suppliers know that (i) they have little negotiating power with regards to terms and conditions and (ii) the solution they create might not be theirs to commercialize.

Table 9 shows that suppliers' main clients do not typically provide technical or financial assistance; however, clients do appear to certify processes, provide technical specifications, and provide technical feedback. Of the eight cases where the principal client had the power to suggest or approve their suppliers' suppliers, six were in the machinery and equipment segment of the value chain; this practice was infrequent in the other segments. Interviews suggested that domestic machinery and equipment suppliers need to provide pieces that fit with original equipment provided by large international suppliers like Caterpillar and Komatsu. Therefore, these international brands insist on having oversight or control of the domestic equipment and services that will be purchased to fit with their original systems. These large international suppliers have the complete trust of their clients (mining firms), allowing them to demand final say on the selection of several tiers of suppliers down the value chain.

Table 9. Relationship with Main Clients

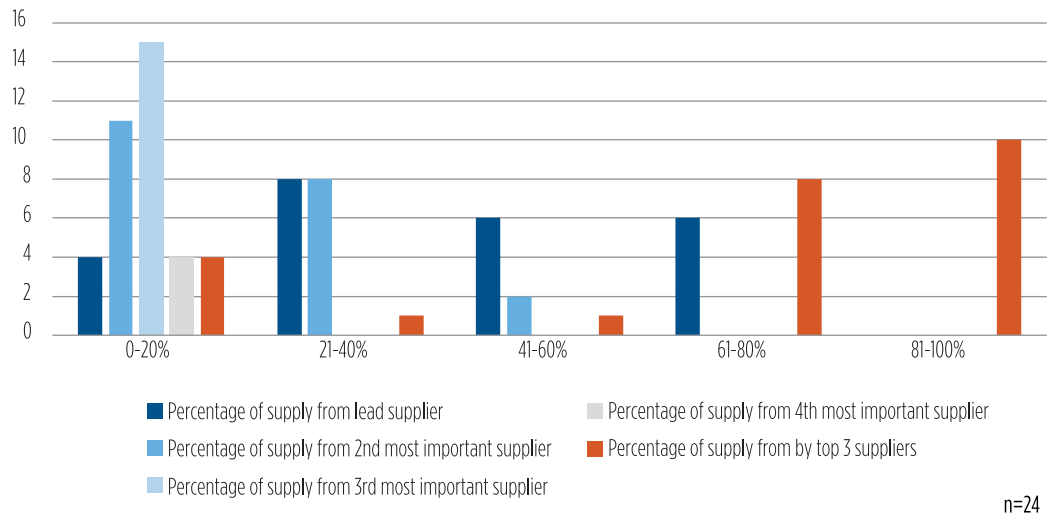
Main client(s)...	No	It Depends	Yes	Total
Has access to your cost structure	13	5	10	28
Provides technical assistance	19	2	7	28
Provides any type of financing	26	1	1	28
Certifies your processes	14	1	12	27
Provides technical specifications	3	5	20	28
Provides feedback	3	2	23	28
Provides information about (non-technical) requirements	9	3	15	27
Suggests or approves suppliers	18	1	8	27
Allows access to the mine(s)	1	0	27	28

Source: Authors' elaboration.

Dependence on Local, National, and International Suppliers

Spending on suppliers is highly concentrated, with 25 percent of respondents indicating that their top supplier accounts for 61 to 80 percent of their purchases and 10 of 24 respondents indicating that their top three suppliers account for 81 to 100 percent of their purchases (Figure 20). Three of the four environmental engineering companies reported that their top three suppliers accounted for 75 percent or more of their purchases, and five of the eight machinery and equipment companies similarly reported that more than 75 percent of supplies came from their top three suppliers. The reasons for these concentrations are different. Environmental engineering firms are relatively small and provide consulting and advisory services and thus need a small range of supplies. Machinery and equipment companies are limited to pre-selected or pre-approved suppliers to satisfy their client(s)' requirements.

Figure 20. Percentage of Supplies from Main Suppliers

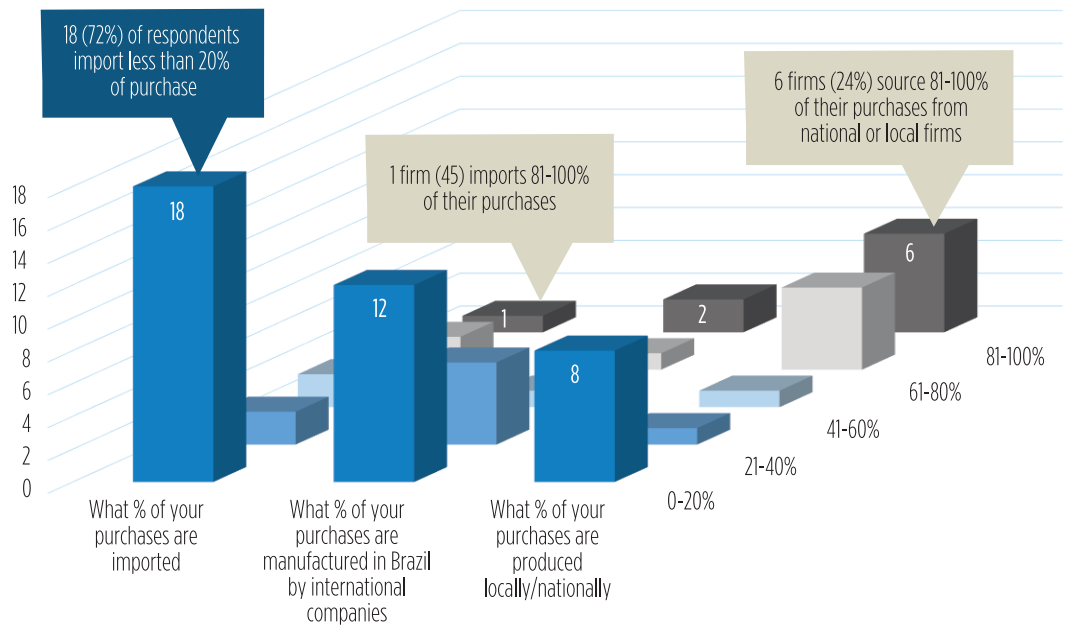


Source: Authors' elaboration.

Figure 21 shows that the vast majority (18) of the respondents imported less than 20 percent of their purchases, with only two respondents indicating that they rely on imports for 80 percent of their needs. This indicates that relatively innovative suppliers can find most of the inputs they need to operate within the domestic market. Although the availability of inputs within the domestic market was rarely mentioned as a barrier to innovation, availability of services, such as testing that clients would see as acceptable, was often mentioned. Notably, supplies available in the domestic market can be (and often are) produced by firms of foreign origin but that are incorporated in Brazil (often referred to as *abrasileiradas*) and thus are not considered imports; however, they cannot be considered domestic innovations either.

In terms of a value chain analysis, it appears that drilling and sampling firms operating in the mineral analysis and economic assessment link of the copper value chain are relatively dependent on imports. Conversely, firms operating in the Extraction and Treatment links tend to source a high percentage of their inputs from local or national suppliers. It is worth noting that mineral analysis and economic assessment firms that are not in the drilling and sampling category also source a high percentage of their inputs from local or national suppliers, suggesting that it is drilling and sampling firms that rely on imports.

Figure 21. Percentage of Input Material Purchases Imported or Made in Brazil



Source: Authors' elaboration.

Drivers of Innovation

As noted previously, the sample for this study was biased toward innovative suppliers. When drivers of innovation were being assessed, responses indicated that these suppliers are primarily driven to innovate by client demand. They are either innovating for their clients or to open up new markets with new clients, for example, by improving their reputation to acquire new clients (Table 10).

Sampled firms confirmed that health and safety is a priority for clients when it comes to requesting innovative solutions. Strict monitoring from regulatory agencies such as the Ministry of Employment create constant demands for health and safety improvements. For example, automated trucks are now used more frequently in mines because they increase safety and lower operating costs.

Table 10. Type of Innovation Activities Reported (n=25)

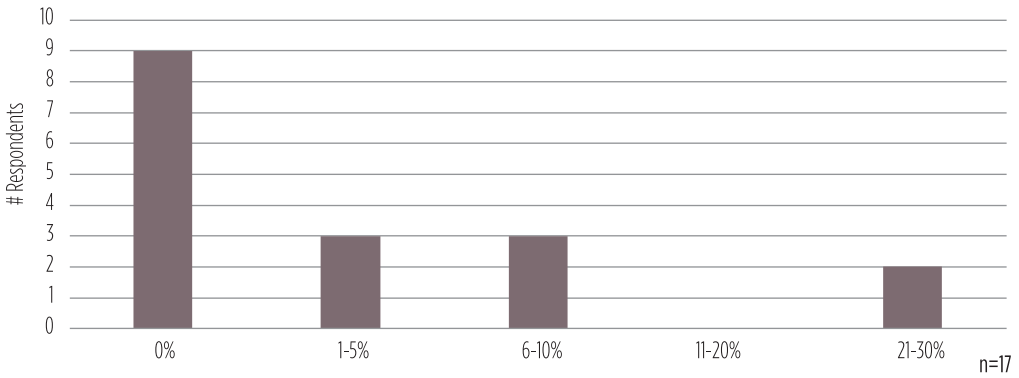
	For Client(s)	For Firm and Client(s)	For Firm
Improve quality	11	8	3
Reduce costs	8	11	2
Solve a technical problem	13	3	3
Solve a health, safety, or environmental problem	14	0	3
Open new markets	3	2	12
Improve reputation	1	8	10
Improve compliance with technical or legal requirements	5	1	4

Source: Authors' elaboration.

Resources for Innovation

Fewer respondents replied to the question about the relative number of staff involved in R&D. We noted that the relative intensity of staff dedicated to innovation and R&D varied considerably, with over half (nine) of the interviewees who responded to this question indicating that their company did not have dedicated staff (Figure 22). At the other end of the scale, two firms had 30 percent of their staff involved in R&D and both were in the IT and Automation category. Three of the six respondents in the machinery and equipment sector had between 5 and 10 percent of their staff dedicated to R&D. The *Innovation Performance* section of this report shows that Brazil in general and the mining sector in particular are not considered particularly innovative. This perspective has been challenged by recent research that suggests mining companies use their vast resources to invest in exploration and expect their suppliers to use more traditional R&D processes to come up with innovations that cut costs, particularly when commodity prices are low (Calzada Olvera and Iizuka, 2020).

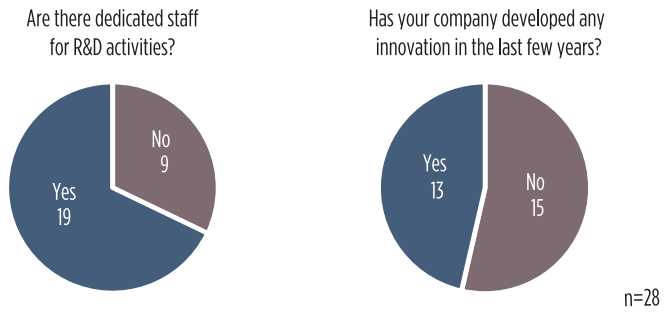
Figure 22. Percentage of Staff in R&D



Source: Authors' elaboration.

The relatively high number of dedicated staff for R&D as well as the number of firms that reported that they had developed innovations recently, showed that the purposeful selection of innovative firms succeeded in identifying companies that valued and invested in innovation (Figure 23). Further, it shows that these firms are perceived by others in the sector as being innovative, demonstrating that companies observe and value the efforts of other firms with regards to innovation. One of the most innovative firms in the sample (in the machinery and equipment category) has a dedicated R&D department that actively obtains patents, publishes in specialized magazines, and secures partnerships with companies that have complementary technologies, often assembling complete solutions for their clients.

Figure 23. R&D and Innovation Staff and Activity (number of firms)



Source: Authors' elaboration.

Types of Innovation Activities

Generally, Table 11 shows that the firms in this study developed more innovations that were new to the firm than new to the domestic market and even fewer that were new to the world. Further product innovations were more common than process innovations, with organizational and market innovations being least common. This is in line with expectations of a well-integrated market that is diffusing innovation from the local ecosystem but also bringing innovation from the global ecosystem into the domestic market. Importantly, it appears that even within this relatively small sample, firms are developing original innovations believed to be new to the world, though it is unclear if those innovations have had a significant impact on economic performance.[19]

19 Comparing data on growth rate in terms of sales, number of employees, and self-reported product innovation, there was no evidence that firms with new-to-the-world innovations had significantly different growth rates than firms focused on new to domestic market or new to the firm innovations (X^2 test p value is 0.629). However, this result is likely due to the relatively small sample size and our deliberate sample bias toward innovative firms.

Table 11. Type of Innovation by New to the Firm, New to the Domestic Market, New to the World

	Product Innovation	Process Innovation	Organizational Innovation	Market Innovation
New to the Firm	22	15	7	3
New to the Domestic Market	20	12	1	3
New to the World	12	3	0	1
Respondents	25	18	7	5

Source: Authors' elaboration.
Note: Respondents could tick multiple categories identifying their innovation activities.

In the next few pages these responses are analyzed in more detail, breaking down the responses by firm category and link in the value chain to identify where there might be higher (or lower) levels of innovation.

New-to-the-World Innovation

Table 12. New-to-the-World Innovation Activity by Firm Category

	Number of Firms in Category	Product Innovation	Process Innovation	Organizational Innovation	Market Innovation
Mineral Analysis (laboratories) in geological research	1				
Mineral Processing (consultancy)	1	1			
Environmental Engineering	4	2			
Process Engineering	1				
Engineering and Construction	1				
Engineering (geology and environmental)	1				
Machinery and Equipment	9	5	3		1
Drilling and Sampling	3	1			
Geology and Mineral Research	2				
Geological Services	1				
IT and Automation	3	3			
Topography	1				
Respondents	28	12	3	0	1

Source: Authors' elaboration.

New to the world indicates that the firm has developed (on its own or in collaboration) an innovation that could be patented or protected as it has a significant novel approach. These types of innovations may differentiate these firms since it may be difficult for other firms to copy the innovations or master the know-how needed to deliver them. Table 12 breaks down new-to-the-world innovation activity by category of firm.

Product innovation was the most common, with firms from five categories reporting innovation that is new to the world, including all three of the IT and automation firms, five of the nine machinery and equipment firms, and half (two of four) of the environmental engineering firms. Only firms in the machinery and equipment category reported new-to-the-world innovation for any other type of innovation, with three of nine firms reporting a process innovation and one reporting a market innovation. It is worth noting that all three firms reporting new-to-the-world process innovation also reported new-to-the-world product innovation, which suggests product and process innovation capabilities may be complementary.

Domestic companies are clearly capable of innovating. Several new-to-the-world innovations by firms in this study were facilitated by links to international business networks that complemented the skillsets of local suppliers and allowed for a full solution to be presented to clients. Many of the international suppliers that partnered with Brazilian companies to provide innovative solutions were from Canada, Australia, South Africa, the United States, and the United Kingdom.

Table 13 presents case studies of new-to-the-world innovation in the machinery and equipment category. The narratives highlight the importance of countering the greater financial might of international suppliers with a deep understanding of client demands, including cultural issues if that provides an advantage. Fostering proximity to the clients, keeping up with the latest technologies, and taking risks are all tactics used by these local innovators. However, risks can unravel a company. Even if a solution is customized for a client, if the client is not willing to buy the service or product, the supplier usually have no recourse because there may not have been a contract. As a result, the supplier might lose the entire investment. Policy levers could provide a safety net or financial support for local innovators, or the state could play role in supporting networking and a secondary market for innovations not covered by an exclusivity contract that need a new buyer.

Table 13. Examples of New-to-the-World Machinery and Equipment Innovations

#ref	Innovation	Success Factors
12	Even before Samarco, the company owned by Vale and BHP that was responsible for the tailings dam incident in Mariana, Minas Gerais, in 2015, everyone knew that the next big thing in mining would be extracting mineral from old tailings dams. We started developing gravimetric separators in 2003 and then other methods to extract more mineral from tailings dams. At that point, everyone was focused on magnetic separation, which caused a bit of a competition between ex-employees. Gravimetric separation finally emerged as the winning model since it focuses on reducing the mineral content of tailings. First, we tried to use gravimetrics by using local equipment, but later we sought the support of a scientist based abroad, where they developed the	One of our clients owned a mine that was no longer active because the mineral content was too low. The proposal was to recycle the tailings dam. The mine was very old—it started operating in the 1960s. Back then the mineral content in tailings was high but pelletization was not available. We experimented first with magnetic separation and then with gravimetrics to further lower the mineral content of the tailings.

#ref	Innovation	Success Factors
12	project combined with a separating belt. Using that technology, the client does not need to put material with high mineral content in the tailings dam. There are companies throwing away waste with 38 percent, 40 percent mineral. We have developed processes with separators and thickeners (making the material thicker in the tailings dam), and now we are looking into filtering. There are great leaders in filtering abroad already, but we are looking into opportunities to work on large projects that involve filtering and centrifuges in order to recover the mineral before it is considered waste. Though with separation you lower the mineral content of the waste, you still need a tailings dam; with filtering you eliminate the need for a tailings dam. The process can be done "dry." There are mines that cannot be worked anymore and where the tailings dam still needs to be decommissioned. If we can help companies recover mineral from the waste in the dam and not return to stacking the tailings, we can free up space where the company can throw away real waste, with a much lower mineral content. Current tailings can be demineralized or the need for a tailings dam could be completely eliminated.	
2	Enclosed carriers, suspension bridge for Vale after Brumadinho, integrated monitoring systems. The suspension bridge we built for Vale has been hailed as an international success story. The bridge replaced the ore conveyor carriers destroyed during the Brumadinho disaster.	We are constantly communicating with clients even if we are not thinking about making an immediate sale. By being close to our clients we know what they need and what type of solutions they are more likely to accept. It is not always the best solution that wins, but the one that fits with the culture of the client's firm. We activated our international partnerships to provide Vale a complete solution. For a domestic company like us, this was big coup. We are one of the few integrators left in Brazil and we have survived thanks to our international partnerships. We always look for technologies that complement ours so that we can present a full solution to the client. We usually seek knowledgeable partners in Australia and Canada.
13	We are developing a project for a large mining firm whose belt scales need regular calibration, which is risky for staff, who often suffer injuries in the process. Two years ago, we provided a first solution. A mechanism supports the belt so the tester only needs to push a lever and move a bit but does not need to carry any weight. A year ago, the firm called us and said, "We don't want to modify the lever. Let's automate the whole process." So, we fitted an engine on the mechanism so that the tester only needs to push a button and the weight pushes the scales to calibrate them. We are now going one step further. A client employee has been cooperating with us to develop a system whereby the tester does not even need to be physically.	Client offering testing facilities, partial funding and a clear challenge.

#ref	Innovation	Success Factors
13	present for the calibration. It can all be done remotely, triggered by an electronic gage that indicates a weight is needed and the mechanism assesses whether the scales are calibrated or not. If we succeed with this development, we eliminate the problem of injured testers. This innovative project has being presented to the client's leadership as a partnership opportunity with us. We are financing a part of this project because we are very interested. We develop the idea and build the prototype, and they provide us with space to do the testing with their machines. We do not have a contract. This is a risky endeavor. It is a matter of taking a risk or not. I like doing this because it means I am ahead of my competitors and, if the project is successful, I'll be the company of choice to upgrade all belt scales in the sector. The client does not demand exclusivity and offers us an entry point to a potential market. If everything goes well, we will recoup our investment and it would pay for itself with new clients.	
18	We develop software for spectral imaging analysis that measures the mineral content and oxidation levels of the ores remotely and provides these data online. Though competitors have equipment for this function that costs millions of dollars, our version is more economic and easier to use. Equipment: – Dynamic Hidrocyclone (new to the world, mix of a cyclone and a centrifuge): Particle size analysis from a sample. – Fourth generation aerator: Used in flotation columns because it produces smaller diameter bubbles, which helps recover more mineral. – Mobile pilot plant: Can be installed in less than a week or remove the plant from any firm. – Vision systems: We are very proud of our combination of imaging analysis and AI. This strong innovation and its Advanced Process Control, and our remote/online systems to measure mineral content, are very disruptive to the market.	– We always aim to innovate in our processes. – The issue of reusing waste (with high mineral content) has created opportunities for innovation. – Sometimes we use equipment that already exists in the market but for different objectives. – It costs money to get rid of the waste (which might also be dangerous) but if we recover valuable mineral content from that waste, then the innovation pays for itself.

Table 14 presents case studies of new-to-the-world innovations in the IT and Automation category. The narratives again highlight the importance maintaining dialog with the client in order to anticipate their needs. In addition, the IT and Automation firms tend to have dedicated resources and even departments for innovation staffed largely with engineers.

These firms are very dynamic and can pivot to serve other industries. Their portfolios of clients are very diverse, and thus they tend to be resilient to crises. Making use of digital technologies was a trend mentioned in both phases of the fieldwork for this study, which points to potential policy levers to support local firms in gaining digital and automation capabilities. Even before COVID-19, mining companies were pursuing automation, increasingly using robots, self-driving trucks, online monitoring of mineral levels, among other technologies. Companies are trying to increase safety, reduce accidents, and reduce labor to reduce risks and costs. This established worldwide trend is now evident in the Brazilian mining industry.

Table 14. Examples of New-to-the-World IT and Automation Innovations

#ref	Innovation	Success Factors
6	Quantitative approaches to management using AI to identify inefficiencies as an ongoing process. Examples: Refrigeration systems for underground mines, optimization of energy usage, and optimization of gold and niobium processing.	– Most staff are engineers. – We tailor solutions to each client using a base software. – Our clients are often surprised at how much money and other resources we save them. – Clients ask us if we can use the same principles on other areas of their firms.
27	We have a fleet management software. Before us, there were two competitors in Brazil. One of our clients became interested in creating an alternative system and asked us to partner with them. We developed the product and launched it in the market. Later we developed a service module to process mineral as well. The solution we provided was more comprehensive, including managing all clients' fleets.	– Capturing clients with stable and predictable revenue – Digitalization of processes – Automation of processes – Because of health and safety issues raised by the tailings dams, we created a system that tracked people.
7	I have a great story: I went to have coffee with a client at their office and we started talking about fleets. They used to hire a third-party to manage their transport and paid them according to the distance the tipper trucks were driving. I asked if it wouldn't be better to monitor the tipper trucks in real time and pay according to those records. My client thought that it was a bit extreme but because he's curious, he went to his records and realized that he was paying over the odds. He asked me to develop a customized system for him, and in six months the client saved 2.4 million Reais.	– The mining tracking software was a feasible innovation because there was scalability and possibilities of customization. – Always being in contact with clients, just to chat, helps us know what they need even before they know it themselves.

Table 15 presents case studies of new-to-the-world innovations in the environmental engineering category. The narratives highlight the importance of partnerships (in this case with universities) to develop innovations, particularly for smaller firms that can then access well-trained scientists that do not cost as much as international scientists. Several interviewees mentioned the high caliber of Brazilian scientists and researchers but pointed out the institutional barriers to make cooperation profitable. Barriers are linked to the possibility of industrial secrets coming out and to disincentives in academia to use public funds to benefit the bottom line of a private firm.

Public policies to create legal models that make it beneficial for both research centers and firms to cooperate would support greater innovative collaborations. One of the respondents was from the firm that predicted that the tailings dam near Brumadinho was vulnerable; we were fortunate to get this interview. The report the engineering firm wrote included recommendations that were not heeded and the consequences were catastrophic. This event did not affect the firm's reputation; it is widely recognized for its expertise, which has helped the business.

Table 15. Examples of New-to-the-World Environmental Engineering Innovations

#ref	Innovation	Success Factors
11	Developed a new method to analyze health indexes within the flora and fauna using drones, more precise decibel meters, and digitalization. The usual way of using a decibel meter is to jot down the results manually, but the new process uploads the data directly into a file. This way there is no way to make errors in the measurements. We now digitalize all of our work. Our firm developed these methodologies but did not publish them. Ideally we should have published them, but the market does not wait.	– Partnerships with local universities to develop projects. – We are always looking for new clients (domestic and abroad) to avoid being overly dependent on Vale, which tends to pay its suppliers after a project has finished.
		– Our clients like that everything we do can be done online and that we provide more credibility to their studies and certificates, documents for licenses.
26	Automated safety system for tailings dams. This program was presented in an international fair and was well received. The program centralizes information, keeps it available online, and emits alerts in cases of anomalies.	After predicting that Vale's tailings dam in Brumadinho was unsafe (report is publicly available), the firm's reputation as a serious engineering firm increased. The firm's automated safety system for tailings dams is in high demand among mining companies in Brazil.

New-to-the-world innovations were also assessed based on their link in the value chain. Figure 24 presents the value chain position of firms reporting new-to-the-world product innovations. Firms were concentrated in the treatment, extraction, and mineral analysis links of the value chain, with less activity in trade, decommissioning, and mineral prospecting.[20] Although several firms confirmed that they also operate in Exploration and Development, they noted that their core activities were Extraction and Treatment. Mining activity in Brazil has a long history, which has supported the development of highly innovative suppliers even in areas requiring higher capital investment, such as machinery and equipment. At the beginning of this study, we expected to find most innovative domestic firms in the highly specialized environmental engineering category given the lower capital investment and intensive knowledge required. Though two of the local innovators worked in environmental engineering, they were not as innovative as those specializing in extraction and treatment.

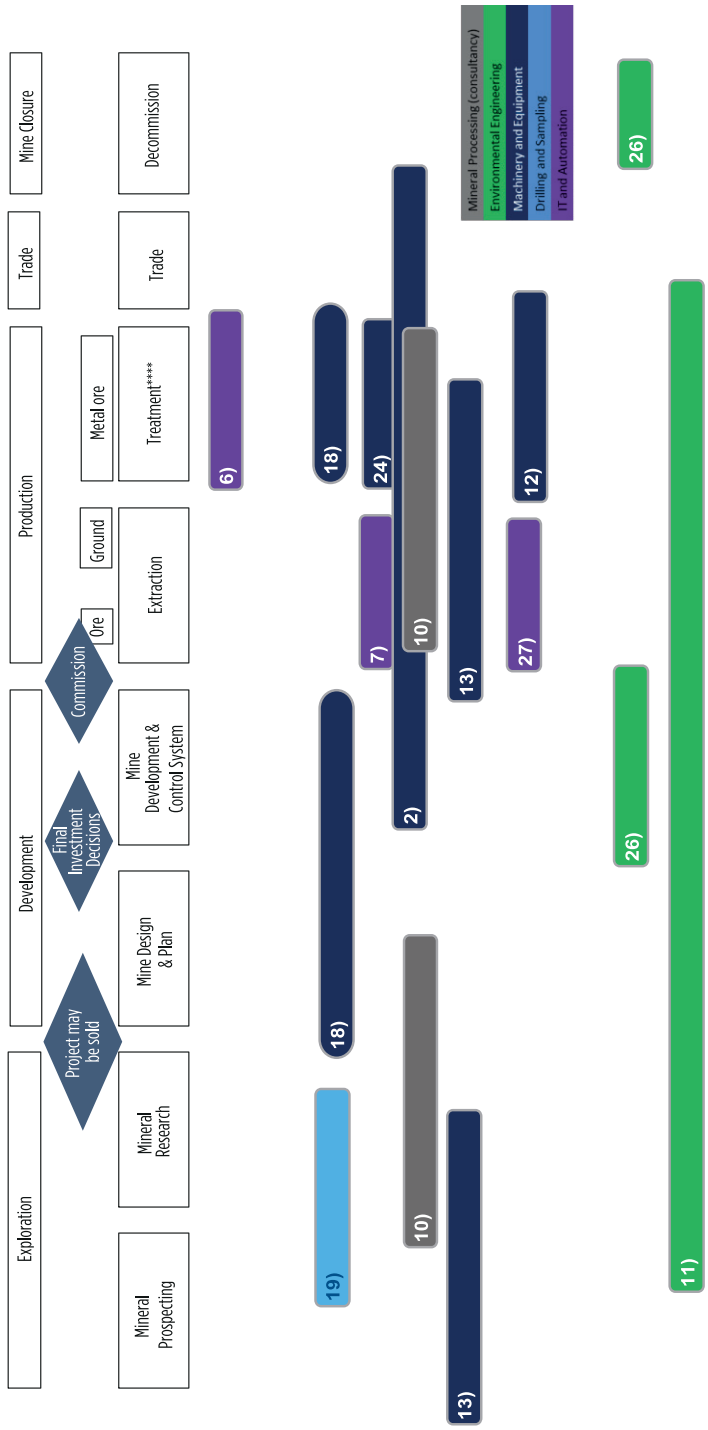
The three firms with new-to-the-world process innovations were all in the machinery and equipment category and concentrated in the Treatment link of Brazil's copper value chain. We learned that process innovation is stimulated by the treatment of new material and by recuperating mineral from tailings and waste, which is geared completely toward processes and encouraged by diminishing world reserves and higher prices for the metal.

We conclude that strongly differentiating innovation is present in product innovation for a wide range of the sector's suppliers and in process innovation mainly for the machinery and equipment sector.

20 Firms can operate across multiple parts of the value chain. We allocated relative activity based on the position(s) in the value chain and the number of firms (12) reporting new-to-the-world product innovations. The score for different parts of the value chain are: Treatment, 36 percent; Extraction, 25 percent; Mineral Research, 14 percent; Mine Development and Control Systems, 11 percent; Design and Plan Mines, 7 percent

There is a caveat to this analysis, however: our sample's bias toward innovative firms reflects a wider bias within the industry. Large machinery and equipment suppliers are perceived to be more innovative because technology is understood to be embedded in machines. This is a traditional bias that still exists as a proxy for innovation in many people's minds.

Figure 24. Value Chain Position of Firms Reporting New-to-the-World Product Innovations



Source: Authors' elaboration. Colour coding is as per Table 7 on page 52

New-to-the-Domestic Market Innovation

New-to-the-domestic market innovation indicates that the firm has the absorptive capacity to search for, adapt, and deploy technology that exists internationally for the domestic market, diffusing international innovative approaches domestically. Table 16 breaks down new-to-the-domestic market innovation activity by category of firm.

Table 16. New-to-the-Domestic Market Innovation Activity by Firm Category

	Number of Firms in Category	Product Innovation	Process Innovation	Organizational Innovation	Market Innovation
Mineral Analysis (laboratories) in geological research	1	1	1		
Mineral Processing (consultancy)	1	1	1		
Environmental Engineering	4				
Process Engineering	1	1			
Engineering and Construction	1		1		
Engineering (geology and environmental)	1				
Machinery and Equipment	9	7	5		2
Drilling and Sampling	3	3	2	1	
Geology and Mineral Research	2	2	1		1
Geological Services	1	1			
IT and Automation	3	3	1		
Topography	1	1	1		
Respondents	28	20	13	1	3

Source: Authors' elaboration.

In product innovation, most categories of firms (except environmental engineering, engineering and construction, and engineering (geological and environmental) showed some level of activity in new-to-the-domestic market innovation, with the IT and automation (3 of 3 firms), drilling and sampling (3 of 3), and machinery and equipment (7 of 9) categories being the most active.

Process innovation that is new to the domestic market is also broadly based in reference to the number of categories represented; however, there are fewer firms active in this area (it is noteworthy that process engineering is not represented). Here machinery and equipment, and drilling and sampling continue to show strong performance. The drilling and sampling sector is the only sector to report organizational innovation (1 out of 3). Finally, in terms of market innovation, geology and mineral research (1 out of 2) and the machinery and equipment sector (2 out of 9) report innovation activity.

New-to-the-Firm Innovation

New-to-the-firm innovation, the most common form of innovation, indicates that the firm can adopt technologies that are available within the domestic market and deploy them within the firm. Table 17 breaks down new-to-the-firm innovation activity by category of firm.

Table 17. New-to-the-Firm Innovation Activity by Firm Category

	Number of Firms in Category	Product Innovation	Process Innovation	Organizational Innovation	Market Innovation
Mineral Analysis (laboratories) in geological research	1	1	1	1	
Mineral Processing (consultancy)	1		1		
Environmental Engineering	4	2			
Process Engineering	1	1			
Engineering and Construction	1	1			
Engineering (geology and environmental)	1	1	1		
Machinery and Equipment	9	8	6	3	1
Drilling and Sampling	3	3	3	1	
Geology and Mineral Research	2	2	2	1	1
Geological Services	1				
IT and Automation	3	2		1	1
Topography	1	1	1		
Respondents	28	22	15	7	3

Source: Authors' elaboration.

Twenty-two firms are active in new-to-the-firm product innovation, with all but two categories represented. Fewer firms are active in process innovation (15), organizational innovation (7), and market innovation (3), which suggests that it is progressively harder to adopt process, organizational, and market innovations even if they exist within the sector. This points to some (potentially short term) competitive benefits from new-to-the-firm activity that cannot quickly be eroded through imitation.

The relatively high level of innovation activity (at least in firms considered to be innovative) points to a sector where innovation can contribute to competitive behavior. Though it is somewhat concerning that some of the environmental, process, and construction engineering sectors are not active in the process, organizational, or market innovation categories.

We found widespread use of digital technologies within the mining companies and their suppliers, including domestic suppliers. Examples include digital systems to manage the entire mining

extraction process, software that optimizes energy use throughout the mining process, exports of software using cloud technology, and using drones for geoanalysis in remote areas. To summarize the imperative to improve and innovate processes, one of our interviewees said:

> "A mine is never the same at the beginning and the end of its operations. The ore changes, the mine becomes harder to work with, and if you don't improve the process, you make the operation non-viable."

Do Clients Facilitate Innovation from Suppliers?

Respondents indicated that most clients (92 percent) had suitable space or facilities for them to demonstrate or trial their products or innovations, thus space does not appear to be a barrier to innovation take-up in the copper mining sector in Brazil (Table 18). However, the vast majority of respondents (92 percent) reported difficulties in demonstrating products or innovations to clients. It is worth noting that the only two exceptions were in the machinery and equipment category. The difficulties faced by suppliers when attempting to demonstrate innovations or solutions to clients (using the clients' spaces) were varied. The relatively conservative organizational culture within large mining clients was often mentioned. One respondent noted that,

> "There's resistance to change. Mistrust on whether it's going to represent a threat to workers. As there isn't a pre-existing purchase authorization, there are delays in decision making."

Generally speaking, respondents expressed frustration with the lack of interest shown by large mining clients when it came to testing innovative solutions. The only time clients were open to testing was if they commissioned the solution or presented a challenge (often in an emergency) to which suppliers could respond. Clients mistrust supplier's expertise and/or commitment to health and safety measures, thinking that suppliers lack the track record with health and safety that large mining companies have spent decades building/implementing. Mining firms and Tier 1 suppliers are genuinely concerned about health and safety as it forms part of the sector's organizational culture. It may sound surprising to observers outside of Brazil, particularly in view of the large industrial accidents caused by the rupture of the Vale dams in Mariana (2015) and Brumadinho (2019), but the Ministry of Employment does monitor health and safety measures in the mining sector. The ministry looks for potential accidents that may affect workers and enforces discipline by issuing fines and sometimes closing mines until remedies are certified. Again, for an outside observer it may seem paradoxical, but not to a Brazilian observer familiar with the decentralized strict monitoring carried out by the ministry all over the country, particularly within large firms.

For some respondents, these concerns are excuses to justify a conservative business culture and a lack of interest in innovating. Other suppliers recognize that they lack the skillset to meet stringent health and safety as well as quality or pricing requirements of large mining firms. This was particularly the case for smaller domestic suppliers, though not for those in the IT or engineering sectors, where their knowledge base was high enough.

Table 18. Type of Innovation Activities

	Yes	No	n =
Do your clients have a suitable space or facilities to test or trial your innovations?	24	2	26
Do you experience difficulties in presenting or demonstrating your products or innovations to your clients?	23	2	25

Source: Authors' data collection.

Another difficulty cited by respondents was competition with universities and foundations, which have lower costs. Arguably large firms may feel less threatened by the possibility of a university or foundation finding a way to commercialize an innovation/solution developed within the physical space of the large firm. In an environment where lack of trust is widespread, competing against non-commercial (but highly innovative) organizations is a serious difficulty for domestic suppliers. In answer to the question about competitors, one respondent noted that,

> "Competition with universities, foundations, because a firm's costs are higher."

Suppliers also mentioned that they need to learn how to price the potential benefits that innovations can bring to the client. Our respondents called those potential benefits "intangibles." It was refreshing to see that some of our respondents recognized how often they failed to put a monetary value on the projected benefits (e.g., reduced costs) for the client in an industry such as mining that is so sensitive to costs.

Another challenge was the fallout of Operation Car Wash (*Operação Lava Jato*), a corruption investigation into the construction and engineering sector. Clients are suspicious of prices being inflated in every budget presented by a supplier. In addition, desperation to win contracts encourages some suppliers to slash prices and present unrealistic project budgets to the clients. In some cases, those that win the project are unable to deliver and those suppliers that quoted more realistically either go bankrupt or are called back to finish an unsatisfactory project that could not be finished by another supplier.

As summed up by one of the machinery and equipment suppliers, the most common strategies reported to overcome these obstacles included "carefully quantifying the expected benefits that the project or innovation could bring to the client." Often owners of mining firms need to be reminded of requirements to adapt to new health and safety and environmental legislations, which requires innovation. Suppliers need to remind clients that, if they do not adapt to new legislation, they risk being forced out of the market or experiencing financial losses. Budgeting very carefully and responsibly might be one of the most important skills for a supplier attempting to convince a large mining company to experiment with a solution. For energy management, using modeling to show the potential benefits more tangibly has paid off. Suppliers require perseverance and need to continually educate clients by showing them how the new solution or innovation could help them save costs or make the process more efficient, among other potential benefits. It is important to recognize that technical officers are often more open to innovations than owners of large firms, who are mostly concerned with immediate profits. Technical officers tend to have a longer-term view of investment in innovations.

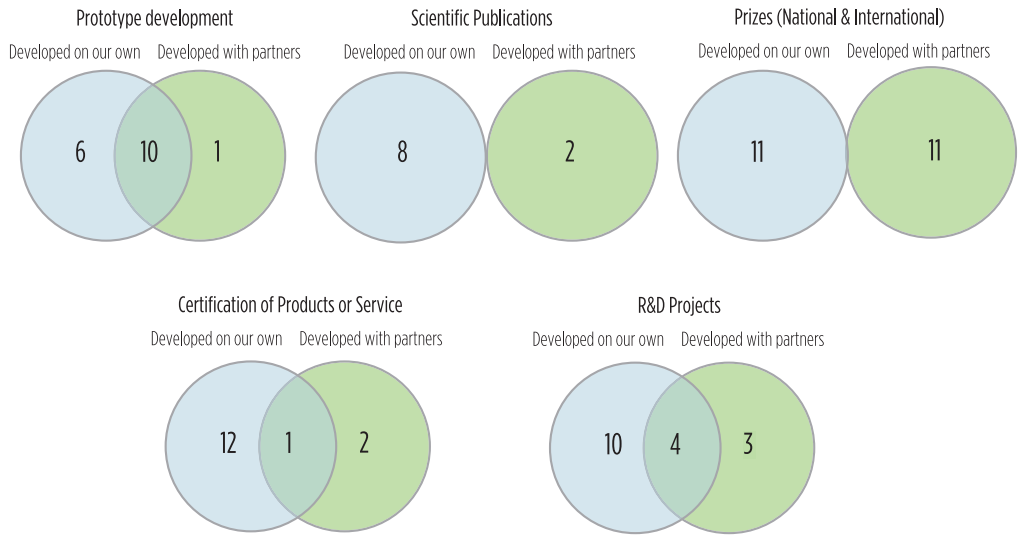
One area where innovation is increasingly required is helping clients find solutions to conflicts with local populations. Suppliers mentioned that one strategy is helping clients increase employment of locals, which goes a long way toward improving community relations.

Financing innovation came up frequently as a barrier for local firms. Mining clients tend to pay only after the project or service has been completed (sometimes 60 days afterward) and some projects may last months or even years. From a cash flow perspective, it takes enormous financial self-sufficiency to work in those conditions and that is one of the reasons many local suppliers have become vulnerable or been absorbed by international companies. Local suppliers have also mentioned that international financing is hard to come by but that partner companies may provide some financing if they are part of the same project bid. Some suppliers had already used financing support from the Brazilian Development Bank (BNDES) and APEX Brasil for innovation. The competition for government loans and credits for local firms is high. Foreign suppliers of machinery and equipment that buy local companies are also eligible to apply.

Extent of the Innovation Ecosystem

The authors observed a relatively well-developed innovation ecosystem in which it is common to consider working with partners on innovation development. Figure 25 shows that innovative projects have incorporated a range of collaboration activities.

Figure 25. Use of Partners and Ecosystem to Develop Innovative Projects in Past Five Years (n=10-18)



Source: Authors' elaboration.

For R&D projects, 10 firms developed projects entirely on their own, 3 worked exclusively with partners, and four had done both, deciding to collaborate on some projects and working internally on others. Notably, Figure 25 also shows more internal R&D than external. IT and automation companies worked exclusively on their own for R&D projects, and machinery and equipment companies showed a preference for working on their own. From a value chain perspective, a visual analysis of firm activities cross referenced against internally delivered R&D shows that R&D is concentrated in the Extraction and Treatment segments of the value chain. These results demonstrate that some of the companies operating along this value chain have sufficient internal capabilities to manage R&D in-house and can draw on those resources to drive innovation.

For prototype development, six firms developed prototypes exclusively on their own, one exclusively developed prototypes with partners, and 10, the majority, collaborated in some cases but not all. These numbers point to an increase in collaboration between the R&D and prototype stages. From a value chain perspective, firms operating in the Treatment link more commonly developed prototypes exclusively on their own.

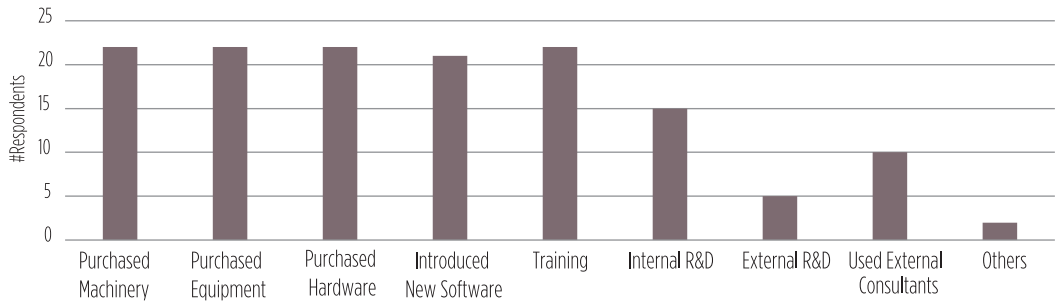
In terms of certification of products and services, 12 firms developing certifications entirely on their own, two exclusively with partners, and one firm having done both. It is noteworthy that the one process engineering firm in the sample systematically adopted a strategy of exclusively developing outputs in collaboration with other organizations and followed this strategy for all product types. This modus operandi likely reflects the need to develop processes in collaboration with clients and suppliers.

For scientific publications, eight firms developed publications exclusively on their own and two worked exclusively with partners, with no firms collaborating sometimes but not always.

Types of Innovation Support Activity

In terms of innovation support activities, the most common were acquiring new machines, equipment, and hardware, though introducing new software and training were also common activities. Figure 26 shows that internal R&D continues to be the more common approach. We note that consulting services are used as another source of external knowledge and know-how to support innovative activity.

Figure 26. Complementary Activities Undertaken to Support Innovation (n=28)



Source: Authors' elaboration.

6. MAIN FINDINGS AND RECOMMENDATIONS FOR POLICY

Main Findings

This study contributes to our understanding of the main opportunities and challenges *in developing a critical mass of innovative local suppliers* in the mining value chain in Brazil. Copper mining was selected for investigation because it would provide a good comparator with other Latin American countries, notably Chile, Peru, and Argentina. Throughout the study, extricating copper-only insights from Brazil was challenging given the way most mining companies and suppliers operate simultaneously with several minerals and the aggregated level at which local statistics are collected.

In Brazil, copper production has not become the key mineral that it is in Chile because the abundance of ferrous metals meant that Vale, the lead mining company, always prioritized iron. Since large companies are clearly well established, particularly in the iron segment, smaller mining companies are now vying for the leading role in other minerals, such as gold and copper. Demand for copper is growing steadily, so new competitors, such as junior and foreign companies, are looking at copper with interest, as demonstrated by the copper investments of Nexa in Rio Grande do Sul, Mineria Vale Verde in Alagoas, and others (see the *Scenarios and Market Trends for Copper in Brazil and Worldwide* section of this report).

The study focused on the exploration, mine construction, and operation stages of the mining process. Given the interest in finding innovative practices, in-depth field research was carried out with local strategic mining suppliers, thus the purposeful bias toward innovative firms in selecting suppliers.

Value Chain Governance

At first glance, governance appears to be diversified in the mining value chain segments where sampled firms operated. In this study, the linkages observed between lead firms and their

suppliers and between Tier 1 and Tier 2 suppliers ranged from captive networks (one firm sets all parameters and controls the other firms in the chain) to arm's length market relationships (based on price, with little flow of information) and included balanced networks, particularly when bidding together for the opportunity to present a joint solution to a client. However, there is a caveat: this sample was biased toward innovative suppliers by design, so the fact that most suppliers had relatively free rein to decide the type of product or solution to offer might be a sign of their well-developed capabilities, which would make a more hierarchical governance model less likely. Nevertheless, even with the innovative firms in our sample, it was common to observe that a foreign firm would provide the more advanced part of a technology or product, whereas the domestic partner would provide the adaptation or supplement to make the solution fit within the local context.

More generally, we noted a strong trend toward the verticalization of supply firms, whereby international companies buy local suppliers (domestic or not) in order to have a larger portfolio of solutions and technologies to offer their clients. This trend was facilitated by the economic crisis in Brazil between 2014 and 2018, which left many local companies in a vulnerable position and therefore attractive targets for acquisition. The larger the type of supplier needed, the more likely it will be a foreign company, which is clearly demonstrated by integrators and large engineering firms that manage projects for mining companies. Very few integrators are domestic, which makes it difficult for other domestic suppliers to be selected as part of the *planilha* (list of suppliers, usually a spreadsheet). It makes more sense to use suppliers that already work with the parent companies based on scale, compatibility of technologies, and trust.

Sectoral Governance and Institutions

As expected in a country with the continental dimensions of Brazil, there is a dense network of institutions and organizations with varied representative, training, and research roles in the mining sector. These entities (public and private) may have national reach with representation in every state of the union or they may be more localized around the mining regions. However, because of Brazil's rapidly changing political landscape and recent economic crises, institutions tend to be very focused on their role serving one link in the chain and tend to lack a more systemic view of the sector.

Notably for this study, which focused on suppliers, one of the main findings from the institutional analysis is that there is no association or register that groups suppliers to the mining sector.

The agency created in 2017 to regulate mining activity in Brazil, the National Mining Agency (ANM), has the important role of licensing and supervising mining exploration and production. The ANM ensures all mining operations follow the legal framework in different areas, such as grants for exploring territory or safety and environmental risk management. However, as a new independent institution, the ANM was still trying to establish itself when the major environmental tragedy of Brumadinho happened. General budget cuts in the Brazilian government meant that the ANM did not have sufficient funding to carry out its complex duties in a country as vast as Brazil and with mining activity spread all over its territory.

Safety Concerns as a Driver for Innovation

Analyzing the safety of tailings dams was not a core element of this research, but it became obvious that accidents such as Mariana (2015) and Brumadinho (2019) focused the industry on providing urgent incentives for innovation related to safety.

Though several of the technologies needed to ensure safer disposal of waste and tailings were available in Brazil before the accidents (dry stacking, filtering, etc.), demand for them is now constantly increasing. Higher demand has created opportunities for local suppliers to promote current technologies plus variations and incremental innovations. Health and safety products and services may now be better received as a result of the heightened sense of urgency to adopt safer and more sustainable ways to deal with waste from mining. At the beginning of this study there were doubts that it would be too early to tell whether safety innovations would be increasing as a result of the tragedies at Vale's mines, but it turns out the industry was ready and the technologies were available.

The mining sector's public image is at an at all-time low, making it difficult for mining companies to recruit the best talent coming out of universities. Not only the environmental disasters have tarnished the image of the sector, but also a generalized perception that the industry is traditional and not interested in innovation.

Innovation by Suppliers

Domestic suppliers are clearly capable of innovating. Several new-to-the-world innovations discussed in this study were facilitated by links to international business networks that complemented the skillsets of local suppliers and allowed for a full solution to be presented to clients.

Although several of the interviewed firms reporting new-to-the-world innovations confirmed that they operate in all segments of the value chain (except trading), their core activity was linked to extraction and treatment. There has been mining activity in Brazil for decades, which has supported the development of highly innovative suppliers even in categories that require higher capital investments, such as machinery and equipment. At the beginning of the study, the assumption was that most innovative domestic firms would work in the highly specialized consultancy for exploration category given the lower capital investment and intensive knowledge required. Although the study found domestic new-to-the-world innovators among consultancies (two firms), they were not as innovative as firms specializing in extraction and treatment.

Among sampled firms, suppliers from a wide range of the sectors were working on new-to-the-world product innovation (strongly differentiating); however, process innovation was mainly being done by firms in the machinery and equipment category. The interviews clearly showed that process innovation capabilities are being stimulated by the need to treat new material and to recuperate mineral from old tailings and waste. Innovations to recuperate mineral are entirely process related and are encouraged by diminishing reserves worldwide and higher prices for copper.

It is important to remember that the study had a sampling bias toward innovative firms (supported by referrals and the snowballing technique). But the bias is broader industry wide than within

the machines and equipment category. Companies in that category are perceived as more innovative because of the idea that technology is embedded in machines; however, this is a very traditional bias that continues to exist as a proxy for innovation for many people.

Nevertheless, an important observation was the relative concentration of new-to-the-world innovation in firms in the treatment, extraction, and mineral analysis segments of the value chain. These segments were also identified as sourcing most of their inputs from domestic suppliers, suggesting that network facilitation programs may be fruitful.

In terms of new-to-the-domestic market innovation, the study shows a healthy innovation cluster where significant parts of the sector are able to bring in innovations and approaches to maintain domestic activities and performance in line with international best practices. Of the 28 firms interviewed, 20 noted that they were working on product innovations and 13 on process innovations, however only one was working on organizational innovations and three on market innovations. The study therefore noted the relatively weaker activities of some of the engineering sectors in process, organizational, and market innovation.

New-to-the-firm innovation was the most common, indicating well-functioning diffusion of technology within the regions where sampled firms are located.

The study highlighted the role of partnerships in developing innovations. Partnerships with universities are particularly important for smaller firms to access well-trained scientists at a lower cost than international scientists. Several interviewees mentioned the high caliber of Brazilian scientists and researchers but pointed out the institutional barriers that make cooperation risky. The concerns include the possibility of industrial secrets coming out and disincentives within academia to use public funds to benefit the bottom line of a private firm.

With regards to innovation partnerships between firms, sampled firms appeared to collaborate most regularly in prototype development and R&D projects, indicating that it is usually beneficial to work closely with a client or research provider for these types of projects.

One of the clearest results of the survey was the difficulties the suppliers had in getting an opportunity to present or demonstrate their products or innovations to clients or prospective clients.

Suppliers in the sample also reported that they needed to learn how to price the potential benefits (intangibles) that innovations can bring to the client. It was interesting—and encouraging—to see that suppliers recognized how they often failed to put a monetary value on projected benefits (e.g., reduced costs) for the client in an industry that is so sensitive to cost reductions.

Finance for Innovation

Financing innovation came up frequently as a barrier for local firms. Mining clients tend to pay only after the project or service has been completed (sometimes 60 days afterward) and some projects may last months or even years. From a cash flow perspective, it takes enormous financial self-sufficiency to work in those conditions and that is one of the reasons many local suppliers have become vulnerable or been absorbed by international companies. Local suppliers have also mentioned that international financing is hard to come by but that partner companies may provide some financing if they are part of the same project bid. Some suppliers had already used financing support from the Brazilian Development Bank (BNDES) and APEX for innovation. The competition for government

loans and credits for local firms is high. Foreign suppliers of machinery and equipment that buy local companies are also eligible to apply.

Supplier–client collaborations can be risky and can cause the unraveling of the local company developing the innovative solution. If the solution is customized for the client and the client is not willing to buy the service or product, then the supplier usually has no recourse. With the possibility that no contract was agreed on in relation to the innovation, the supplier might lose all of their investment.

By keeping part of their production in Brazil and the rest abroad, foreign companies (or local companies owned by foreign firms) are better protected from crises. They are also more agile in reducing their presence in Brazil to a minimum when the economy is contracting, returning and expanding as conditions improve. Some Brazilian suppliers have aimed for those levels of internationalization in order to have a diversified client base and be more resilient to crises, but still only a minority.

Contracts between clients and suppliers put enormous pressure on suppliers. Respondents referred to such contracts as an unavoidable risk, meaning that they accepted them because otherwise they would not make the sale. This indicates a power imbalance that hinders innovation because the supplier knows that the solution they create might not be theirs to commercialize.

This links to the issue of intellectual property barriers. Initiatives such as the Mining Hub are trying to overcome such barriers by making all solutions available to all members of the Hub. The goal is to follow the principles of open innovation, which is easier to do as Mining Hub members are dealing with collective challenges that affect the whole sector.

New Technologies

We found widespread use of digital technologies within the mining companies and their suppliers, including domestic suppliers. Examples include digital systems to manage the entire mining extraction process, software that optimizes energy use throughout the mining process, exports of software using cloud technology, and using drones for geoanalysis in remote areas. To summarize the imperative to improve and innovate processes, one of our interviewees said:

> "A mine is never the same at the beginning and the end of its operations. The ore changes, the mine becomes harder to work with, and if you don't improve the process, you make the operation non-viable."

Worldwide, significant investment has been made to automate the mining industry (Daly et al., 2019) and Brazil is no exception. Even before COVID-19, mining companies were pursuing automation, increasingly using robots, self-driving trucks, online monitoring of mineral levels, among other technologies. Companies are trying to increase safety, reduce accidents, and reduce labor to reduce risks and costs. This points to potential policy levers to support local firms in building digital and automation capabilities so they do not fall behind because of a lack of resources to upgrade and acquire these capabilities. Of note, resources include the need to improve the education of the workforce in order to be able to absorb new technologies.

Policy Recommendations

Mining is a mature sector in Brazil that has been receiving government and private sector support for decades. The relatively large institutional network is capable of carrying out activities such as research, lobbying, innovation, and financing. All recent governments have sought to design and implement (with varying degrees of success) public policies aimed to support development of the mining sector.

Despite those accomplishments, the mining sector is still fragile, as demonstrated by the human and ecological tragedies at Brumadinho and Mariana. The message was clear: existing support was not sufficient to prevent tragedies. Something needed to change and the mining sector needed to upgrade as a whole with regards to safety, technology, and communication with all sectors in society.

Within that context, and using this study's findings as a starting point, some suggestions for policy are presented below. Though these suggestions were grouped according to the research objectives, this artificial separation is purely for analytical purposes—the measures are intrinsically linked.

Some suggestions discussed below have already been espoused by sector leaders and are part of local debates. What is proposed here, however, is an attempt to collate and to amplify those local debates, finding ways to link and integrate initiatives that might not be widely known or are incipient.

Sectoral Governance, Institutions, and Image

The renewal of the social license for the mining sector depends on firms being proactive about ensuring tragedies do not happen again. Mining companies also need to show the public that their efforts are genuine. Simultaneously, the mining sector needs to improve its engagement and communication with local communities and with the general public by explaining the role of mining revenues in local development through taxes, direct employment, and the creation of local demand for goods and services. If the mining sector wants to keep attracting top talent, it needs to clearly show and communicate its commitment to environmental safety, innovation, and supporting the communities that host mines.

The sector's governance needs to be improved by promoting ethical practices and safety through self-regulation within the sector to avoid future accidents and reduce environmental impacts. By investing in research and promoting innovation, Brazilian mining companies could become international leaders in safety and disposal of mining waste. Though this endeavor will require investment, mostly it needs a great interinstitutional effort of coordination. Some firms and local governments (e.g., Minas Gerais) have started this trend by using open innovation principles to support their innovation efforts, specifically the Mining Hub.

External regulation and monitoring could accelerate the uptake of innovations in tailings dam safety, and thus health and safety regulations could be of use to reduce workplace accidents. It tends to be external agencies (i.e., not linked to mining) that oversee industrial health and safety in large companies. Our interviews showed that these agencies are respected and their sanctions are feared. Our hypothesis is that part of the success in monitoring health and safety comes from the external

nature of the monitoring agencies: the Ministry of Employment and trade unions. Another reason for the ministry's success in monitoring health and safety is that they are financially self-sufficient and independent of the mining sector. Traditionally, trade unions were very strong in Brazil and a source of bargaining power for formal, full-time employees of large companies (both mining companies and large suppliers). Although their power is not what it used to be (Brazil modified employment regulations), unions can still scrutinize mining practices. However, trade unions do not protect informal workers or contractors, or some employees of small and medium enterprises.

A key recommendation is to strengthen the ANM. It is important to secure sufficient funding to ensure the ANM can monitor and enforce regulations with independence, effectiveness, and efficiency. The high number of mines and tailings dams that need to be monitored is a huge challenge that can only be overcome with a well-resourced, agile structure with low levels of bureaucracy. The goal is to achieve the ANM's original objective of bringing about a disruptive institutional modernization of the mining sector by taking over the role of the National Department of Mineral Production, which no longer exists. The ANM's role would also be facilitated by a greater commitment from firms to fulfill their environmental and social responsibilities. The ANM should also deploy digital technologies to streamline processes.

The Brazilian Mining Institute (IBRAM) has started to set up a sector-wide technical committee to spearhead the repositioning of the mining sector, but it will need a wider and more comprehensive membership. Such a committee could include workers and representatives of the sector's diverse stakeholders, whose voices have yet to be formally included. During one of the most important sector events last year, serious concerns were voiced about the lack of representatives from the communities affected by the mining disasters either among the presenters or discussants. As long as there is no open dialog about social license, it will be difficult to achieve lasting consensus.

Investments by mining companies in their host communities have had positive impacts on local development. However, in light of the recent mining accidents, these investments are no longer perceived to be enough to compensate for the risks. Therefore, it is important to effectively communicate the social and economic benefits of mining activity alongside renewed commitments to safety. This communication could be led by the sector-wide technical committee suggested earlier or by other actors (e.g., government), but it is a key measure. As some mining leaders know, this type of campaign cannot be rushed because if it is not based on genuine internal change, it can expose the sector to yet more (justified) criticism and it will entrench negative attitudes. Timing is of the essence; such a campaign can only be designed and implemented after some real changes can be communicated.

Another (longer-term) way of improving the sector's image would be to promote greater social control over the use of mining royalties (CFEM) and to support municipal governments in creating local economic development programs to mitigate the effects of mining closures.

Any stakeholder interested in strengthening the mining sector should be involved in ensuring CFEM is used as intended: to create sustainable projects to ensure a better future for mining municipalities. Critical discussions of how CFEM is used (not necessarily for the benefit of the local populations) are common in national and local media outlets, contributing to the negative perceptions about the impacts of mining on society at large.

Support for Suppliers

The mining sector clearly needs to create an association of suppliers. Even if a large proportion of suppliers do not work exclusively for the mining sector, mining clients are very important and contribute a sizable portion of suppliers' revenues. More accurately knowing the size of their markets could help both mining firms and suppliers refine their strategies and focus their innovation efforts. Such an entity would need to be integrated with the suggested sector-wide technical committee.

A first step toward creating an association would be to compile a register of suppliers. In order to support local suppliers to the mining sector, policymakers need to know how many firms there are, their characteristics, whether they have diversified away from mining because of a lack of supportive policies or whether other sectors are their objective and mining is just one of many options. A supplier register is a medium-term project that would need to be embedded into a wider strategy of sector development and with a clear strategy to communicate how suppliers would benefit from participating in this register.

One way to entice suppliers to participate in a register and knowledge-exchange events would be the prospect of providing input to the design of a supplier development program for the mining sector. Currently, procurement managers are cautious and do not take chances on untested local suppliers. The prospect of a register might be more appealing if it is the first step toward creating supplier development programs and a policy to engage with local universities and vocational training to improve human capital. A well-designed communication strategy is key for these endeavors to succeed, and we found that communication in general within the sector and between its main actors needs improvement.

One suggestion would be to promote a training program about pricing the value of innovation, aimed at domestic suppliers. The goal would be to teach suppliers how to sell the future value of investing in innovation to a sector that is very much preoccupied with short-term cost reductions.[21]

Given that smaller mining firms and smaller projects might be the new normal for copper and other non-ferrous minerals, a good opportunity for policy might be supporting smaller consultancies that can grow with these new projects and develop new techniques for non-ferrous metals.

Industrial Policy

Brazil has yet to formulate an industrial policy for mining that has been properly discussed with all stakeholders in society and that aims for a sustainable production model. Nowadays there are different policies and resources for the sector, but they lack coordination or at least more interinstitutional links between the different initiatives. This lack of coordination among the sector's support measures fosters a sense of instability and risk (institutional and legal) that discourages potential investments.

Multilateral organizations and development agencies such as the Inter-American Development Bank (IDB) could have a role to play by offering incentives to adopt a sectoral culture of putting the social license of mining at the center of any investment, which must promote the highest safety and sustainability goals. Investments in infrastructure should prioritize social (including safety) and

21 For example, see courses by the millerheinmangroup.com, although there could be Brazilian alternatives.

environmental concerns and, by making remote mining locations more accessible, could help lower the costs of considering a more nationally integrated value chain for minerals such as copper.

As the ministry responsible for policymaking in the mining sector, the Ministry of Mines and Energy has a key role in liaising with national (e.g., the ANM) and international (e.g., the IDB) organizations to review current policies. The ministry's recommendations would enjoy sector-wide credibility, although they will need to foster partnerships with stakeholders to ensure implementation. Indeed, in July 2020, the Minister of Mines and Energy, Bento Albuquerque, announced that a National Mining Plan would be launched before August 2020 (Agenciabrasil, 2020). We hope this plan will provide a baseline for further improvements and recommendations like the ones presented in this report. We expect to see policies that deal with energy efficiency, incentives to use alternative sources of energy (one of the main costs of mining is energy), reducing emissions, and promoting more efficient water usage.

The Brazilian debate on mining has featured long discussions about the need to reduce the industry's dependency on iron by increasing the exploitation of other minerals and natural resources. Stimulating more research, updating the geological service to improve the accuracy of reserve mapping, and developing new ways to raise funds from public and private sources are key tasks that any mining strategy should cover. Tax incentives already exist for research, which are used mostly by large firms. Other types of incentives are needed for start-ups and small and medium enterprises. Also, the Canadian model of promoting citizen investments in shares of mining projects and firms using the stock market should be investigated.

With regards to copper specifically, it is important to have a wider discussion about the advantages and disadvantages of linking the two ends of the value chain: producing the mineral and transforming it into the metal. While government agencies exhort the advantages of connecting the whole process with arguments about value addition, mining firms do not see it the same way, since earnings from producing copper concentrate (the powder exported to be transformed in smelters abroad) are higher than transforming it into the final metal locally.

Research Development and Innovation

Broadening the innovation debate is another endeavor that appears both urgent and inevitable. Even in today's difficult economic context, resources need to be directed to applied research. Elements of the open innovation approach need to be incorporated into solutions for issues that affect the entire mining sector equally (e.g., safely managing mining waste and water management).

Promoting technical partnerships between companies, universities, and technological centers (e.g., CETEM in Rio de Janeiro and SENAI's center for innovation in Belo Horizonte) is a clear policy opportunity considering evidence of collaboration to develop prototypes and for R&D projects. The study showed that the mining sector respects scientists and wants to cooperate with them even more. However, institutional barriers hinder collaboration between universities and companies. Policymakers should evaluate the regulatory framework for universities and technological centers to find ways to ensure: (i) the security of firms' industrial secrets, (ii) fair compensation for universities and technological centers, (iii) possibilities for publishing and patenting, and (iv) creative solutions

and communication strategies to address the ethical conundrum of publicly funded bodies helping private firms innovate and potentially increase their profits.

As suggested by value chain literature, policies to support acquiring process and functional capabilities (higher value-added capabilities beyond manufacturing) and functional upgrading are needed.

More should be done to facilitate the diffusion of innovation within the industry in Brazil (new-to-firm innovations), such as policies to support networking and open innovation accelerators such as the Mining Hub.

Suppliers would welcome policies to create opportunities for firms to share their knowledge and their solutions. Mining firms should be encouraged to share knowledge about common challenges affecting the industry, launch innovation challenges, design performance indicators (financial, environmental, and social), and promote dialog about regulations, monitoring, education, and training policies as well as engagement with the wider community. These endeavors could enhance non-competitive communication and collaboration between the entities representing different subsectors of the mining value chain.

In this regard, supported by public policies, the Mining Hub in Belo Horizonte could inspire similar initiatives elsewhere. The Mining Hub offers an open innovation environment, matching top mining firms and suppliers, providing space to test prototypes or services, and maintaining a business acceleration program for small solution providers. Similar initiatives could work in Porto Alegre (considering the Nexa project in Caçapava do Sul and the concentration of machinery and equipment suppliers in the south of Brazil), Rio de Janeiro, São Paulo, and Pará. We are not suggesting that the new hubs should be exact replicas of the one in Belo Horizonte; each program should consider local factors. Even in Belo Horizonte, slightly different open innovation and accelerator initiatives have appeared for mining suppliers, one of them funded by SENAI.

With regards to intellectual property associated with innovations developed with suppliers, IBRAM and ADIMB could have a role to play. Mining firms are not going to give up their rights to innovations that they have funded; however, for innovations funded by a supplier, there should be a pathway toward registration and commercialization by the supplier. New ways of negotiating intellectual property issues could be discussed in working groups and, once there is agreement, an informal norm could arise for the sector. IBRAM and ADIMB could also host events clearly linked to innovation diffusion, not only within the Mining Hub but on other occasions and during mining events to show their commitment to this push toward innovation in the mining sector (the Women in Mining movement is a precedent for other industry-wide initiatives).

Innovations are often the result of investments in capabilities and time spent experimenting with solutions with the same client. Unfortunately, mining companies tend not to give much notice or commit to certain levels of orders with their Tier 2, usually domestic, suppliers. Mining firms seem to treat these future demands for innovative solutions as industrial secrets. It would be beneficial to have public policies that support the flow of communication between mining companies and their suppliers so suppliers can plan their production, investments, and recruitment ahead of time.

With regards to innovation partnerships between firms, sampled firms appeared to collaborate most regularly in prototype development and R&D projects, indicating that it is usually beneficial to work closely with a client or research provider for these types of projects. Innovation activity

focused on health, safety, and environmental issues; technical problems; improving quality; and reducing costs.

As an international development bank, the IDB could have a role to play in financing suppliers developing innovative solutions. Examples from other industries in Latin America show that lead firms in value chains can finance their suppliers using a variety of mechanisms (Navas-Aleman, Pietrobelli, and Kamiya, 2015) and such mechanisms could be adapted to suit partnerships for innovation in mining.

The Future

Brazil's northern state of Pará is thought to be the next big cluster of development and innovation in mining. The largest iron ore mine in the world, Carajás, is based in Parauapebas, Pará, and owned by Vale. This mine also extracts copper and other minerals such as gold, bauxite, nickel, and manganese. The area has large reserves and has already attracted large firms, such as Vale and its Tier 1 suppliers. Many of the suppliers are international companies that have opened offices and factories in the municipality of Parauapebas. Given the quantity and quality of the mineral endowments, even a small operation in the area could be a good opportunity, as demonstrated by Oz Mineral, Lara, and Vale Verde.

In the state of Rio Grande do Sul, Nexa (a merger between Votorantim [Brazil] and Milpo [Peru]) made a large investment in Caçapava do Sul in 2014. If everything goes to plan, the company will be mining copper, lead, and zinc by 2024.

These two areas present different scenarios for policy support. Pará is very remote, providing an opportunity to start a cluster development strategy from scratch, including energy, infrastructure, and investment incentives. Also, the remoteness makes it imperative to invest in local human capital. Rio Grande do Sul is one of the most technologically advanced areas of Brazil, with a dense network of machinery and equipment suppliers and some of the best universities and technological institutes in the country. The challenge here is to ensure that local suppliers are quickly linked to Nexa to make it less attractive to bring in suppliers from abroad. In both clusters, the government has the opportunity to create collaboration networks for innovation and supplier development programs aimed at local companies, and to test new, cleaner, and safer technologies in the post-Brumadinho era.

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Perspectivas atuais da indústria de cobre no Brasil (Brazilian Copper Industry's current perspectives)	BNDES Setorial nr. 36, s.d. (National Bank for Economic and Social Development) (https://www.bndes.gov.br/SiteBNDES/bndes/bndes_pt/Galerias/Convivencia/Publicacoes/Consulta_Expressa/Tipo/BNDES_Setorial/)
Desenvolvimento e inovação em mineração e metais (Development and innovation in Mining and metals)	BNDES Setorial nr. 43, s.d. (National Bank for Economic and Social Development) (https://www.bndes.gov.br/SiteBNDES/bndes/bndes_pt/Galerias/Convivencia/Publicacoes/Consulta_Expressa/Tipo/BNDES_Setorial/)
Balanço das Portarias de Lavra, 2017 e 2018 (Mining Ordinance Balance, 2017 and 2018)	Secretaria de Geologia, Mineração e Transformação Mineral - SGM - MME (Secretary of Geology, Mining and Mineral Transformation- Ministry of Mining and Energy) (http://www.mme.gov.br/web/guest/secretarias/geologia-mineracao-e-transformacao-mineral)
Plano Nacional de Mineração 2030 National Planning for Mining 2030	Secretaria de Geologia, Mineração e Transformação Mineral - SGM - MME (Secretary of Geology, Mining and Mineral Transformation- Ministry of Mining and Energy) (http://www.mme.gov.br/web/guest/secretarias/geologia-mineracao-e-transformacao-mineral)
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Release - Indústria Mineral (Release - Mineral Industry)	ABDI - Agência para o Desenvolvimento da Indústria no Brasil (Agency for Industrial Development in Brazil) (www.abdi.gov.br)
Sondagem de Inovação - 4º Trimestre 2017 4º Trimestre 2018 (Innovation Survey - 4º quarter 2017, 4º quarter 2018)	ABDI - Agência para o Desenvolvimento da Indústria no Brasil (Agency for Industrial Development in Brazil) (www.abdi.gov.br)
Lista de Produtos da Indústria - PRODLIST 2016 (Industry Product List - PRODLIST 2016)	IBGE - Instituto Brasileiro de Geografia e Estatística (Brazilian Institute of Geography and Statistics) (www.ibge.gov.br)
Matriz de Insumo Produto Brasil 2015 (Input matrix product Brazil 2015)	IBGE - Instituto Brasileiro de Geografia e Estatística (Brazilian Institute of Geography and Statistics) (www.ibge.gov.br)
Pesquisa Industrial - PIA Produto 2016 *Industrial Research - IR Product 2016)	IBGE - Instituto Brasileiro de Geografia e Estatística (Brazilian Institute of Geography and Statistics) (www.ibge.gov.br)
UN Comtrade	https://comtrade.un.org/

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