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How does innovation take place in the mining industry? Understanding the logic behind innovation in a changing context

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How does innovation take place in the mining industry? Understanding the logic behind innovation in a changing context

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Abstract

Mining activity has been contributing to the income of resource-rich developing countries but it has also been considered as a "curse" for economic development. Reviews of a literature from innovation perspective reveal that the sector has the following mutually-influencing constraints on innovation: a) the commodity price is volatile and exogenously-determined, leaving no scope for differentiation; b) mining firms have low incentive for investing in knowledge (e.g. research and development (R & D)) due to low appropriability; c) development of mines require large, upfront, and long-term investments, leaving no room to take additional risks; d) mining firms tend to operate in an enclave, with limited backward and forward linkages; and e) comparative advantage is largely determined by the presence of mineral deposit not by productive capability. This study aims to bring together evidence to understand the innovation mechanisms in the mining sector. We uncovered that innovation and linkages in mining sector are closely related to commodity prices as follows: a) mineral exploration, a risky, knowledge-intensive investment to increase mineral supply that leads to profit, is equivalent to R&D; b) mining firms increase the exploration and R&D investments when the mineral prices rise; c) mining firms rely on innovation by the suppliers to reduce production cost; and d) mining firms increase the use of suppliers when mineral prices fall. The better understanding of innovation mechanism in mining sector enables to formulate effective policies to make the sector to be a catalyst in transforming the economy of resource rich developing countries.

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Keywords: the resource curse, mining, innovation, economic development, extractive industry

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1. Introduction

There has been a widespread perception that natural resource-based activities, particularly the mining industry, are a curse for economic development. This perception has been formed based on researches from international trade, employment, and industrial development (Prebisch, 1950; Singer, 1949; Hirschman, 1958; Sachs & Warner, 1995, 2001). Recently, the role of the mining industry in economic development has been given a renewed attention from an innovation perspective. Innovation[1] is essential in improving productivity, which would bring about economic growth. OECD countries had been stimulating innovation through policy intervention. However, historically, these innovation policies had been designed based on experiences from manufacturing sector, and they lack understanding on the mining sectors. Therefore, it is critical to increase our understanding of how innovation takes place in the industry, where basic assumptions are different from those in the manufacturing industry. Indeed, the interplay of several characteristics of the mining sector pose challenges in the quest to achieve higher levels of productivity and economy-wide technological upgrades through innovation.

Innovation in the mining industry is important for several reasons. Firstly, from an industry perspective, innovation is necessary to tackle the fundamental challenges encountered by mining operations worldwide, such as the decentralisation of activities, decreasing ore grades, and the increasing social and environmental costs that reflect the growing concerns of civil society and pressure from regulations. Secondly, from a development perspective, innovation is necessary for extending linkages to convert the sector from being the "enclave". Thirdly, from a transformational perspective, the increasing use of digital technology can not only improve productivity and linkages, but can also help in expanding the possibility for lateral migration to other non-mining activities, potentially generating knowledge spillover effects (Lorentzen, 2008). In this regard, innovation not only tackles existing problems but also acts as a catalyst, generating broader impact via diffusion, and building linkages using new technologies upon which the process of economic development hinges.

For natural resource-rich countries to grow effectively, understanding the innovation processes in mining sector is critical, especially to take advantage of the expanding horizon of digital technology. However, innovation mechanisms in this sector generally remain understudied. Recent literature provides an insightful understanding of the innovative potential of the natural resource

[1] It is defined as "a new or improved product or process that differs significantly from the unit's previous products or processes and that has been made available to potential users or brought into use by the unit (process)" (Organization for Economic Co-operation and Development (OECD) / European Statistical Office (EUROSTAT).

sector for developing countries, and the key role that suppliers play from case studies (Iizuka et al., 2019; Andersen et. al., 2015; Morris, Kaplinsky, & Kaplan, 2012; Pietrobelli, Marin, & Olivari, 2018). However, these do not lay out a general understanding of the innovation mechanism of the mining industry, which are not only different from those pertaining to manufacturing, but also from other natural resource industries, such as agriculture or fisheries.

Moreover, the sector has gone through a series of important changes. Some of these changes are the globalisation of activities via extended value chains, as well as the application of digital technologies. The commodity super-cycle that occurred at the beginning of the third millennium exposed the industrial transformations that have existed in the industry for decades. The presence of new technologies, particularly digital and environmental, augments at each phase of production with an ever-increasing potential. These new conditions lay out a different policy context for the mining sector. This study intends to shed light on the innovation processes of the mining sector and on the impact of the various changes that the industry has undergone, and to outline a sober perspective of the potential of the industry.

This paper is structured in the following manner: firstly, it briefly reviews the literature on the natural resource curse, paying special attention to instances that refer to innovation and linkages to understand sectorial idiosyncrasies in the present-day context. Secondly, building on the unique features of the mining sector, we propose two hypotheses on innovation and linkages. Thirdly, this paper presents a compilation of evidence stemming from the analysis that is based on available secondary data sources. These are then presented to validate two hypotheses and to establish a current understanding of innovation mechanism in the mining sector. The last section concludes, reflecting on the newly-unveiled understanding of the mining sector, and exploring policy implications with reference to the resource curse and the future development of the mining sector.

2 Literature review: resource curse, linkages, and innovation

2.1 The resource curse: from an economic perspective

The extractive industry has often been considered a "curse" for development. While the curse stems from the relationship between natural resources and poor development observed in empirical works (e.g., Sachs & Warner, 1995), several rationales have been put forth to explain these economic outcomes. There are two categories of the said curse: economic and political. We focus on the former category in this brief review[2].

The most prominent argument for subpar economic performance in natural resource-rich countries is the Dutch disease; a phenomenon in which high commodity prices lead to the appreciation of the exchange rate, which subsequently discourages growth in other export sectors (especially in the manufacturing sector) present in the country (Corden & Neary, 1982). Another important argument is that the volatility of commodity prices leads to unstable macro-economic conditions, which ultimately lead to poor economic performance (Deaton, 1999; Mikesell, 1997; Moradbeigi & Law, 2016; van der Ploeg & Poelhekke, 2008). Van der Ploeg and Poelhekke (2008) explain that in resource-rich countries, commodity price volatility leads to negative liquidity shocks. This volatility discourages investment and hampers innovation and growth.

Moreover, over-reliance on commodities for government revenue, and the deteriorating terms of trade (exporting inferior goods, such as commodities, and importing superior goods, such as manufactured items) causes long-term trade imbalance, which reduces prospects for economic growth (Prebisch, 1950; Singer, 1949; Sachs & Warner, 1995, 2001). Commodities are easily replaced by other exporters or by new technology and products, as they are quite sensitive to changes in price. Likewise, mineral extractive sector tends to operate in enclaves, creates very few forward or backward productive linkages, consequently resulting in not generating effective employment, neither a favourable economic impact (Hirschman, 1958).

Recent literature in development economics questions some of the above claims of the resource curse. Existing empirical studies present unconvincing results concerning the negative terms of trade argument. For instance, inconclusive results were obtained when using slightly different indicators (Brunnschweiler, 2008; Cuddington, 1992; Ellsworth, 1956; Tilton, 2013), the periods covered (Cuddington, 1992; Ellsworth, 1956), and methods of analysis (Brunnschweiler, 2008). Similarly, critics from the historical and institutional perspective argue that the provision of human capital, physical infrastructure, and institutional capability have been omitted from

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2 In discussing the context in which resources are used, there are valuable contributions from political and economic literature that explain the negative consequences of natural resources on the governance of a country, stemming from the control of its access to these natural resources. These studies explain the contextual differences from a historical, social, and political perspective to understand the differences and similarities of the developmental outcomes of resource abundance. Though this is certainly a valuable question, our study focuses on understanding the sectorial contributions to development stemming from innovation mechanisms. In the case of mining, these are highly linked to productive linkages, such as suppliers and other mechanisms of an economic nature. For a thorough discussion of economic and political mechanisms that explain the resource curse, see Badeeb, Lean, & Clark, (2017) and Frankel, (2010).

explanations of the link between trade and growth. These studies increasingly question the validity of claims based on evidence and data presented earlier at the macro level.

Studies from the policy perspective claim that institutional mechanisms, such as Sovereign Wealth Funds (SWF) or the Economic and Social Stabilization Fund, are effective in absorbing volatile commodity market prices and exchange rates to maintain macroeconomic stability (Collier, 2010). Others have discovered that the presence of highly skilled human resource and a presence of natural resources improve productivity, indicating that the presence of education and research facilities may enable a country to take full advantage of natural resources (Bravo-Ortega & Gregorio, 2007; Ville & Wicken, 2012). The above study suggests that the mere presence of natural resources is not to be blamed as the only cause of the resource curse. Instead, it points to the possibility of lack of complementary assets (human resources, financial mechanisms, institutions, etc.) as the factors that hamper the effective utilisation of natural resources for economic development.

Several historical case studies have demonstrated that mining activities can propel the diversification of the economy and create knowledge-intensive jobs when supported by sound institutions and policy interventions (David & Wright, 1997; Upstill & Hall, 2006; Urzúa, 2012; Ville & Wicken, 2012). These studies suggest that natural resources can be an asset in economic development given enabling conditions, such as suitable human capital, physical infrastructure, knowledge (science, technology, and innovation), institutions, and policies, to establish more productive pathways. Nevertheless, the literature on the natural resource curse fails to mention the micro-level perspective on firm level innovation, knowledge creation, and diffusion in relation to the developmental process.

2.2 Discussion on innovation and mining

Innovation contributes to development in two ways: improving productivity and diversifying activities via spillover effects. Despite its potential, innovation process of the mining sector, with specific reference to sectoral characteristics, is understudied. According to the Pavitt Taxonomy of innovation (1984), the mining sector is largely characterised as "supplier-dominant innovations."[3]

[3] One of the early studies that can be linked to extractive industries with innovation is Pavitt (1984). This study, which was done based on UK data from 1945 to 1979, classified "agriculture, traditional manufacturing industries, and housing" activities as "supplier-dominant innovation" (these industries depend on suppliers to generate innovation for cost-cutting as they have limited means to appropriate knowledge). This category does not specifically mention the mining sector. However, the basic characteristics of the mining sector are more closely associated with the "agriculture, traditional manufacturing industries, and housing" sector than other sectors listed below.

Under this category, firms rely on suppliers as the source of innovation. Firms in predominantly traditional manufacturing industries, such as textile and agriculture, are typically placed in this category in the original Taxonomy (Pavitt, 1984). The goal of a supplier-dominant innovator is cost-cutting because users of their products are price sensitive. Furthermore, the knowledge upon which this type of innovation is based has a low level of appropriability. This means that it is costly to profit from knowledge generated from its diffusion and broader application; hence firms are less inclined to invest in research and development (R&D).

Innovation in the mining sector shares the characteristics of "supplier-dominated innovation" (Pavitt, 1984). The reasons for this stem from the idiosyncrasies of the mining sector. Firstly, mining firms are, fundamentally, commodity producers. Commodity prices are fixed by the market with little to no room for product differentiation and price alterations (Filippou & King, 2011). Considering that profits are generated from the difference between the market price and production costs, the aim of innovation in this sector is ultimately focused on cost-cutting to maximise profits. Secondly, innovation in the mining sector often takes place in a specific geographical space (often in remote regions of the country), forcing mining firms to overcome location-specific challenges. These challenges include a combination of physical infrastructure such as the availability of road, water, and electricity; and geological conditions such as ore grades, efficiency in the use of explosives, and equipment that can be used in varying altitudes (Bravo-Ortega & Muñoz, 2015; Kaplan, 2012). These innovations pose a challenge for broader application by limiting the scope and scalability of the spillover effect. Moreover, these innovations are embedded in the processes, along all the phases of mining operations (i.e., prospection & exploration, extraction, processing, closure, and remediation) rather than in the product (i.e., minerals). Hence, the appropriability of knowledge is, in general, obscure. These characteristics make

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- **Supplier-dominated**: includes mostly firms from traditional manufacturing sectors (textile and agriculture, which rely on sources of innovation external to the firm, such as suppliers. Users of these products are price sensitive (as with commodities), and the goal of innovation is cost-cutting.
- **Scale-intensive**: characterized mainly by large firms producing basic materials and consumer durables (such as the automotive sector). Sources of innovation may be both internal and external to the firm having a medium-level of appropriability. Users are price sensitive. The goal of innovation is cutting costs and product design.
- **Specialized suppliers**: smaller, more specialized firms producing technology to be sold to other firms (specialized machinery production and high-tech instruments). There is a high level of appropriability due to the tacit nature of the knowledge required, and so the use of patents becomes prevalent. Users are performance sensitive. The sources of technologies are customers and are developed in-house. The goal of innovation here is product design.
- **Science-based**: high-tech firms that rely on research and development (R&D) from both in-house sources and university research, including industries such as pharmaceuticals and electronics. Firms in this sector develop new products or processes and have a high degree of appropriability from patents, secrecy, and tacit know-how. The sources of technologies and the goal of innovation are mixed, but the bulk of innovation is supplied in-house.

the investment in knowledge risky for mining firms. As a result, individual mining firms are less likely to invest in knowledge (Nelson, 1959; Metcalfe, 1995), leaving these tasks to suppliers with versatile areas of activities.

Notwithstanding the above characteristics, there are some examples of innovation that overcame the challenge of low applicability and resulted in sector-wide productivity gains. These demonstrate some potential for the sector to contribute in development process. Some notable examples are listed below:

- The technology involved in drilling for deep sea oil in Norway (Upstill & Hall, 2006);
- The technologies used to liquefy oil to allow long-distance transportation in Australia (Ville & Wicken, 2012);
- Advanced coal-washing technology in South Africa (Kaplan, 2012; Pogue, 2008);
- Open-pit mining technology in the United States (US) (Urzúa, 2012; Wright & Czelusta, 2004) which was used to overcome the poor quality of deposits/ores, among other geographically specific challenges;
- Introduction of solvent extraction electrowinning (SX-EW) technology in copper to overcome degrading ore quality (Bartos, 2002).

Thirdly, the industrial characteristics of the mining sector restrict, and strongly shape, the pattern and type of innovation. For instance, the mining sector requires a huge upfront investment for the exploration and construction of mines in the early phase of their life cycle (Collier, 2010). The initial investment entails infrastructure and large, specialised machinery that usually lasts over 30 years (Bartos, 2007). Such a large investment would exert significant stress on mining firms if they had to take additional risks by obtaining new technology, equipment, and financing options. As a result, they often look for less innovative and already-proven technology. Furthermore, the early phase of mining operations nowadays is managed by large global service providers such as Engineering, Procurement, and Construction (EPC) companies, or Engineering, Procurement, Construction, and Management (EPCM) companies, which determine the type of equipment, technological solutions, and suppliers required without much consideration for local spillover effects (Bramber et al., 2019; Bartos, 2007).

2.3 Discussion on linkages and mining

For a long time, mining has been considered an enclave activity, with limited spillover effects that can help generate a broader economic impact (Hirschman, 1958). The mining sector was considered to having used fewer suppliers (i.e., no backward linkages nor upstream linkages) than in other sectors, and even when suppliers are used, they are often of foreign origin, thus generating limited spillover effects in the local economy (Dietsch, 2014). A growing body of literature illustrates several changes that are taking place with respect to the backward linkages in developing countries. As mineral deposits occur naturally, the locational choice of operation by the intended users is not made on the basis of comparative advantages of the productive capability of stakeholders at the location. In other words, the mining sector can potentially provide a good opportunity for local suppliers to upgrade via participating in the mining global value chains (GVCs) provided that these suppliers have the capabilities to respond to the demands of the large-scale mining firms, or *majors*, (Pietrobelli & Rabellotti, 2011). This section reviews the potential and challenges in this.

Firstly, the wave of globalisation has resulted in the mining activity moving away from a high level of vertical integration of inputs and services to global outsourcing (Urzúa, 2012; Korinek, 2013). The increasing reliance of the mining sector on outsourcing and the specialisation of mining suppliers have been widely observed in the past two decades (Urzúa, 2012; Scott-Kimms, 2013). This was further augmented by the increase in foreign direct investment, market liberalisation, and the advancement of technology that lowered logistic costs. These led to the building of a complex web of global value chains in the mining sector (Humphrey & Schmitz, 2002; Diestche, 2014; Urzúa, 2012; Scott-Kemmis, 2013). International input-output data identified a substantial increase in the exchange of services along the GVCs (Kolwaski et al., 2015), and the mining sector was not an exception in such global trends (OECD, 2019). While this is true, as explained in the previous section, the strong role of EPC and EPCM companies limits the participation of local suppliers and shapes the types of innovation that can be introduced in the later phases of the life cycle of mines (Bramber et al, 2019).

Moreover, a closer look at the types of mining suppliers helps differentiate the contractual relationship with mining firms amongst them. The suppliers providing large capital equipment (such as machines, trucks, grinders, etc.) are largely oligopolistic, where a few firms dominate approximately 50% of the market (Commission Nacional de Productividad, 2017, Bramber et al, 2019). These suppliers form collaborative relationships with *majors*, at the global level to minimise costs and provide efficiency for the miners in exchange for a guaranteed market for the suppliers. As explained later, the mining firms take different approaches with the conventional and emerging mining suppliers.

Secondly, the idiosyncrasy of the mining sector poses several challenges in forming sustainable linkages involving local suppliers within the mining sector (Urzua et al., 2016; Iizuka et al., 2019). Mining firms have historically preferred short-term profitability over long-term productivity gains. This dates back as early as 1949, when productivity and coal prices in the US coal industry showed an almost-perfect negative correlation (Kuykendall & Qureshi, 2014). This has occurred in 1904 as well, when documents described the best practice of the mining industry as withholding investments in new equipment as much as possible as "the patchwork character of additions to […] equipment will make up for the inefficiencies of the operation" (Warren, 1939, p. 22). In recent years, the industry has focused relentlessly on short-term profitability, that is, the financial performance over a couple of years (Deloitte, 2017), exacerbating this behaviour with respect to innovation and contributing to subpar productivity levels. For example, the mining firms' procurement decision is largely controlled by the headquarters, and tends to adopt incremental and ad hoc, ready-made, proven technological solutions from established local suppliers (Pavitt, 1984; Atienza, Lufin, & Soto, 2018; Bradley & Sharpe, 2009). This gives limited opportunities for small-scale local suppliers without a track record of success or established business relationships (e.g. a spin-off from the majors) to participate in the value chains. Moreover, the lack of experimental use or a testing ground to demonstrate suppliers' prototypes is often mentioned as one of the reasons for the limited success of local suppliers to negotiate with the majors (Urzua et al., 2016). The suppliers are also often isolated, smaller in size, and suffer from power asymmetry. Latin American cases of local suppliers demonstrated that the risks and costs of innovation are absorbed almost entirely by the suppliers as they lack negotiation power with majors (Figueiredo & Piana, 2016, 2017; Molina, 2017). This leads to transactional, rather than collaborative interactions between large miners and local firms, hampering the innovation process (Pietrobelli et al., 2018).

Despite the above difficulties, there are some successful cases of local mining suppliers. Often, these cases require the presence of strong institutional support by the public sector, such as state-funded specialised research centres, as evidenced in the US or Australia (Calzada Olvera, 2018; Scott Kemmis, 2013; OECD, 2019). In fact, several countries have established a local content requirement policy (Korinek & Ramdoo, 2017)[4]. Likewise, building capability (such as the institutional and systematic ability to take advantage of resource endowment) is much needed in many resource-rich emerging countries (Morris et al., 2012; Andersen et al., 2015, Acemoglu &

[4] Despite generating local employment, the extent of the effectiveness of local contents policy in productive development is highly debatable (Korinek & Ramdoo, 2017). These tends to focus on low hanging activities and not on knowledge intensive activities that concern productivity upgrading.

Robinson, 2012). However, some local suppliers have managed to integrate themselves into the value chain even without institutional support. These are often found on services and products that are highly customised and cater to local specific needs (Molina, 2017; Stubrin, 2017).

Although a less risky and less innovative route is preferred by mining firms, new avenues are opening for the mining sector with emerging technologies, ranging from geo-mapping to self-driving (WEF, 2017; Bramber et al., 2019). These employ new technologies, such as 3D printers, drones, and other digital innovations (Calzada Olvera, 2018). Morris et al. (2012) suggest that under a positive commodity price environment, better provision of information and communications technology (ICT) can generate higher externalisation of activities that can eventually lead to the building of new collaborative linkages between mining firms and innovative emerging suppliers. Environment-related innovation, such as ecologically non-invasive techniques, renewable energy, and water treatment technologies represent another area with similar potential. For example, Vale's tailings dam incident in 2019 generated strong incentives for developing new technology to treat tailings, which is now considered as the major challenges on a global scale (Global Tailings Review, 2020). For identifying local suppliers in emerging areas, the majors often apply "open innovation" strategy, in which mining firms explore outside the usual boundary for solutions using pecuniary (e.g. patent) or non-pecuniary mechanisms (e.g. boot camps, hackathons, etc.) (Chesbrough & Bogers, 2014). The new areas of activities entail lateral or horizontal linkages that allow technology to migrate between sectors (Lorentzen, 2008). For instance, innovation using ICT for better logistics, the efficient use of water, and renewable energy generation are beneficial for other sectors as well as the local community. All the above lead to the potential creation of broader spillover effects.

This review section translates into three points. Firstly, natural resources, contrary to conventional thinking, have the potential for development through the enhancement of productivity via innovation, and extending productive linkages of suppliers. Secondly, the potential for innovation is found in mining service suppliers that employ new technologies, responding to local specific needs that essentially reduce the costs of operation. Thirdly, although the peculiarity of the industry poses challenges, the development of linkages is essential for development, especially if the activities have wide applicability that allow suppliers to migrate or diversify into different segments beyond the mining sector.

3. Hypotheses and research questions

Generally, innovation contributes to economic growth by enhancing productivity in two ways: upgrading productivity and generating spillover effects. As stated above, mining firms' preference for short-term profitability over long term productivity gains, combined with the degrading ore grades and the exhaustion of productive mineral deposit sites, have translated into a substantial drop in productivity worldwide, specifically in countries like Australia, Canada, and the US (EY, 2017a, 2017b). Enhancing productivity in the mining sector via innovation is now inevitable.

Productivity is generated either by adding value or reducing costs. Spillover effects materialise as economic growth when value networks are created through backward linkages, or via linkages which migrate laterally into broader areas of economic activities. In both cases, local systems (stakeholders, institutions, and systems) serve as a conduit of knowledge by connecting a diverse set of related actors. In order to capture innovative activities, research and development (R&D) expenditures and patents are often used as the codified indicators of innovation, although it is well established that innovation can take place without R&D (Huang, Arundel, & Hollanders, 2010). This is especially applicable to the mining sector as it uses location-specific and highly intangible knowledge that has low appropriability.[5]

In general, firms try to maximise their profit. To achieve this at the firm level, a firm needs to maximise revenue and, at the same time, reduce costs. Revenue in mining firms is generated by the unit price of minerals and the volume of mineral production. The profit (P) is derived from revenue after subtracting the production costs (C), which consist of fixed costs (FC) and non-fixed or variable costs (VC(x)). Fixed costs typically include the cost of infrastructure, capital equipment, wages, and those expenditures that will not depend on the volume being produced. On the other hand, variable costs change with the amount of mineral produced (x). These include input materials and additional wages caused by the increase in production. This relationship is expressed in the equation below:

$P(x)=R(x)-C(x)$, where $C(x)= (FC) + (VC(x))$, and $R(x)=Pr \cdot (x)$,

[5] In a later section, this study utilizes R&D expenditure and patents to illustrate some trends. This is strictly due to the availability of certain indicators. Authors are fully aware that this is not all the knowledge employed in the mining industry.

where P is profit, R is revenue, and C is cost. Price is Pr, and it is considered exogenous due to its commodity-driven nature. Hence, revenue is largely determined by the market and a firm can only influence its revenue by adjusting the volume of production (x). Under such restrictions on revenue,

$$P(x)=(Pr \cdot (x))-(VC(x)+FC),$$
$$P(x)max=(Pr \cdot (x))\ max-(VC(x)+FC)\ min$$

In the mining sector, some of the key peculiarities are: 1) price (of the mineral) is exogenously set, and 2) the proportion of the fixed cost to total cost is larger and more speculative than in the conventional manufacturing sector. The price of commodities is exogenous, and firms have no control over the price[6]. This implies that the only means left for a firm to change revenue are: either a) increasing the volume of production without increasing costs; b) increasing the efficiency of mineral deposits by finding more productive deposits; or c) reducing the cost of production to a minimum by reducing fixed costs (e.g. the introduction of new equipment, and organisational changes). This means that innovation should ultimately be aimed at these three objectives. Table 1 summarises potential areas of innovation to maximise profit in mining firms and provides specific examples to illustrate this.

By using the equation above, it is possible to assume that to maximise profits, the volume of minerals should be maximised. However, this would only take place when the market expands or when prices are increasing. Otherwise, the additional volume of minerals would not always increase profits without simultaneously decreasing the cost of production. Furthermore, attempting to increase the volume of production is critical as mineral ore grades decrease with the increasing impurity of harmful substances (e.g. arsenic in the case of copper) that are costly to the process. Based on the logic behind profit-maximising for firms, it is possible to hypothesise that the search for more productive mineral deposits (i.e., exploration activities) would increase when the price of minerals is on the rise. It is also possible to assume that mining firms' investment in R&D for

[6] In the case of the manufacturing sector, firms invest in R&D to differentiate between products because the price is decided by the market as a result of competition. The characteristics of innovation in the mining sector are distinctive from those of the manufacturing sector. In the mining sector, innovation is not related to the conventional "value addition" in terms of increasing the perceived value of the product, having a distinguishing feature from similar products (differentiation), or augmenting the implicit quality appreciated by consumers (i.e., brand image). These aspects do exist in minerals (e.g. certifications and international standards concerning environment and labor conditions), but they only add marginal value to mineral commodities because the end-use of minerals is inconspicuous at the moment. This means that incentives for innovation and the appropriation of knowledge are substantially lower in the mining sector. These conditions, however, differ in mining suppliers as the quality of inputs and services are important to be a part of the GVC and get business from big miners.

exploration purposes would increase with the increase in exploration activities, which are often carried out by mining firms as well as service suppliers, or *juniors*.

> H(1): Mining firms increase exploration activities to expand mineral production when the mineral price is rising so that they can maximise profits. (Consequently, innovation, expressed as R&D investment and patents for exploration, also increase when prices increase).

As already mentioned, another way to maximise profits is by reducing the cost of production. This option is preferred when market demand is weak and prices are low. Under such circumstances, there are stronger incentives to reduce costs. Since variable costs diminish with reduced production, firms are especially likely to reduce fixed costs, as they incur these regardless of production volume. This pressure to reduce variable costs would be stronger when the market is expanding (and there is corresponding expansion of volume). However, the pressure would be substantially weaker if the increment in commodity prices is high enough to offset the current level of variable costs. The literature review reveals that this sector relies on service suppliers for cost-reducing innovation by solving local specific problems or challenges (in line with Pavitt's taxonomy). This suggests another hypothesis; when the price of minerals decrease, cost-reducing innovations by, or with, suppliers will increase in the mining sector. This type of innovation may accompany the strengthening of linkages or the use of suppliers by the mining firms.

> H(2): Mining firms increase the linkage with suppliers (backward linkages, in terms of input and output analysis) when mineral prices decline to carry out cost-reducing innovation (customisation, the introduction of digital technologies, etc.) and to maximise profit. Consequently, suppliers' innovative efforts, calculated by patenting activities, become larger than that of mining firms, and it increases counter-cyclical to commodity prices.

Table 1. Possible areas and actors of innovation to maximise profit in mining firms

Maximise				Minimise			
Possible actions taken		Who does it?	Example	Possible actions taken		Who does it?	Example
Volume of mineral				Fixed Cost			
Find deposit with higher grade	Exploration: search for better deposits to increase efficiency and meeting demands	Junior or Mining firms	Employ remote sensing, satellite systems; deeper exploration	Labour Cost	Replace labour with technology; employ the business model to reduce accidents.	Collaboration with established suppliers of the sector, e.g. Komatsu with Rio Tinto in developing self-driving excavators.	Self-driving large equipment, introduction of digital devices for managing labour
				Physical Infrastructure	Introduced at the early phase; Employ new technologies for services that can be added	EPC, EPCM, Suppliers	Renewable energy, desalination plants
				Capital equipment	Collaborative R&D with oligopolistic large international suppliers; alternatively, open innovation with small domestic suppliers if it is location-specific, tailor-made services	Collaboration with established large suppliers; small-scale producers responding for local needs, incorporating digital technologies	Automotive mining machines, customised building structures, use of drones for high altitude or underground
				Replacements, parts, daily maintenances	Collaborative R&D with established suppliers, mostly large scale but can also be small scale when it is location-specific	Collaboration with established suppliers; high tech start-ups for customised equipment producers responding to local needs	Timely replacement (e.g. tires, grinders, etc.); customised adjustment, non-invasive inspections (e.g. pipes, pumps,), surveillance drones
				Logistics	Efficiency in delivery; less energy or less environmental impacts	Local suppliers	New truck formation for shortening loading time
				Digital platform	Introduce new management systems	Emerging suppliers (start-ups or large scale)	Management systems or labour, inputs
				Environment and social	Organisational and technological (digital) solutions	Global suppliers for solutions that requires scale, local suppliers for location specific solutions	Global suppliers provide solutions for tailing treatment and renewable energy generation local: dispute settlement with the indigenous population

Source: Authors' elaboration

Building on the features of innovation in the mining sector from existing literature, we derived two hypotheses concerning innovation within this industry. Firstly, we assume that mining firms invest and engage directly in innovation through explorations (in a pro-cyclical manner to commodity price). Secondly, we assume that innovation is adopted mostly through third parties (suppliers) in a counter-cyclical manner to reduce costs. In the following section, we provide a compilation of evidence to support our hypotheses on innovation patterns in the mining sector.

4. Discussion of innovation particularities in mining

4.1 Exploration: the core of innovation in the mining industry

Expenditure for exploration is akin to R&D in the sense that it is a high-risk activity with the commercialisation process left to be explored. According to Kreuzer & Etheridge (2010), having access to new deposits in the mining sector is the equivalent of developing a new "product," especially if the discovery involves better quality deposits (higher grade, easier processing, and strategic locations). This is because the development of such deposits can greatly improve productivity through cost reduction in processing, and it allows for the expansion of production volume. Therefore, the expenditure on exploration is like that of R&D expenditure in manufacturing, although such expenditure may not be formally recognised as R&D.

While cost-cutting is of prime importance, mining firms are willing to maintain high levels of expenditure for exploration and evaluation of future mining sites as these secure future rents. Due to the high costs involved in exploration, it makes sense for mining firms to engage in this activity when future market prospects are high. Moreover, it is also true that exploration costs have increased substantially in recent decades because easily-accessible deposits are already being exploited, leaving the more problematic ones available for exploitation (Schodde, 2003). As it is highly probable for mineral deposits to be closely located geographically, brownfield exploration, which is exploration around already-exploited sites, is preferred when mineral prices are uncertain. This would substantially lower the risk and costs related to greenfield exploration (S&P, 2017).

Figure 1 demonstrates the positive relationship that exists between the profit and investment of the 40 largest mining firms (by revenue) during a period that includes the fall and then the recovery of commodity prices reflected by the profitability of its operations. Investments (which include exploration, projects and property, and other technology acquisitions) began with USD 100

Billion in 2008 and ended with a figure representing roughly half of that in 2016; illustrating that despite a mild delay, the industry is quite pro-cyclical in its investment (Bramber et al., 2019).

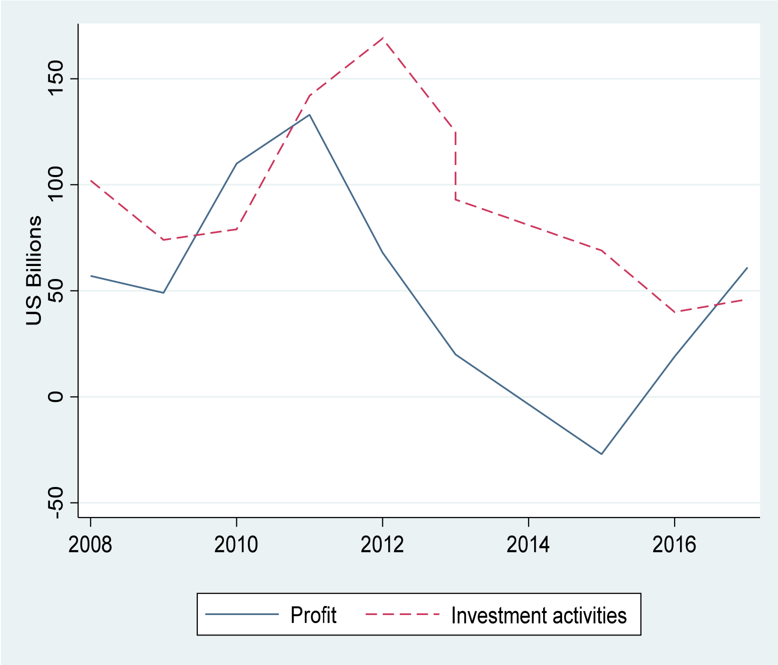

Figure 1. Aggregate profit, exploration, and capital investments for the top 40 firms are reported in each edition. Period 2008–2017 (USD billions)
Source: Authors' elaboration with data from PWC, 2018.

Figure 2 shows the average exploration investments vis-a-vis R&D of BHP Billiton, Rio Tinto, Anglo American, and Glencore from 2003 to 2018. It is evident that exploration expenditures have increased parallel to commodity prices, and these are substantially higher than that of R&D investments. R&D has followed a similar pattern to investment activities as shown in Figure 2, though on a lower scale, showing a mild but steady growth from the initial levels in 2003. This is consistent with the conclusions of Daly et. al. (2019), whose data indicates that the R&D investments of mining firms show similar pro-cyclical behaviour in Europe. More generally, data from OECD countries show that mining firms had invested in business enterprise research and development (BERD). On aggregate terms, it also shows the increase with the commodity prices in a pro-cyclical manner. The degree of investment in R&D in the mining sector, however, varies greatly across countries. Countries like Norway, Chile, and Mexico have invested relatively small amounts in comparison to Canada, Australia, or the US (where BERD is generally high to start with). Among these countries, Canada has shown slight increments while the US has substantially increased its R&D investment, making it the country with the largest R&D investment in the mining sector among OECD countries. Australia, on the other hand, has dramatically reduced its investment level in the mining sector (OECD, n.d.). Even with the reduction, Australia, the US and China still retain very high levels of investment in R&D in the mining sector (Valacchi et al., 2019). However, as can be seen in Figure 3, the lion's share of R&D investments in mining comes from China.

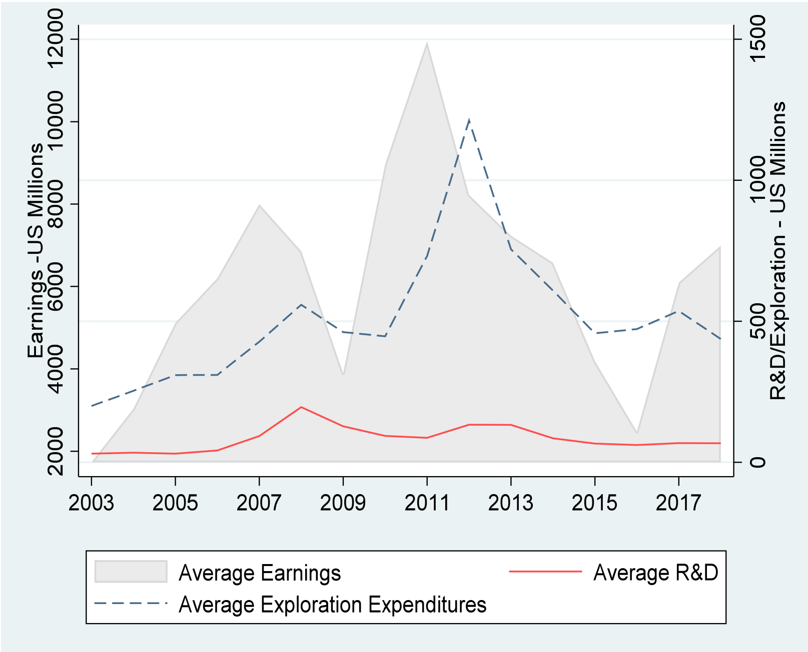

Figure 2. Average R&D (red line) and exploration investments (blue dotted line) for the largest mining firms: BHP Billiton, Rio Tinto, Anglo American, and Glencore from 2003–2018 (USD millions)

Source: Authors' elaboration with data from firms' reports.

As can be seen in Figure 3, the BERD levels have increased in the last two decades. Recent empirical data shows further details about the mining R&D efforts such as the fact that they are largely concentrated on exploration and that they are carried out by the METS (Valacchi et al., 2019).

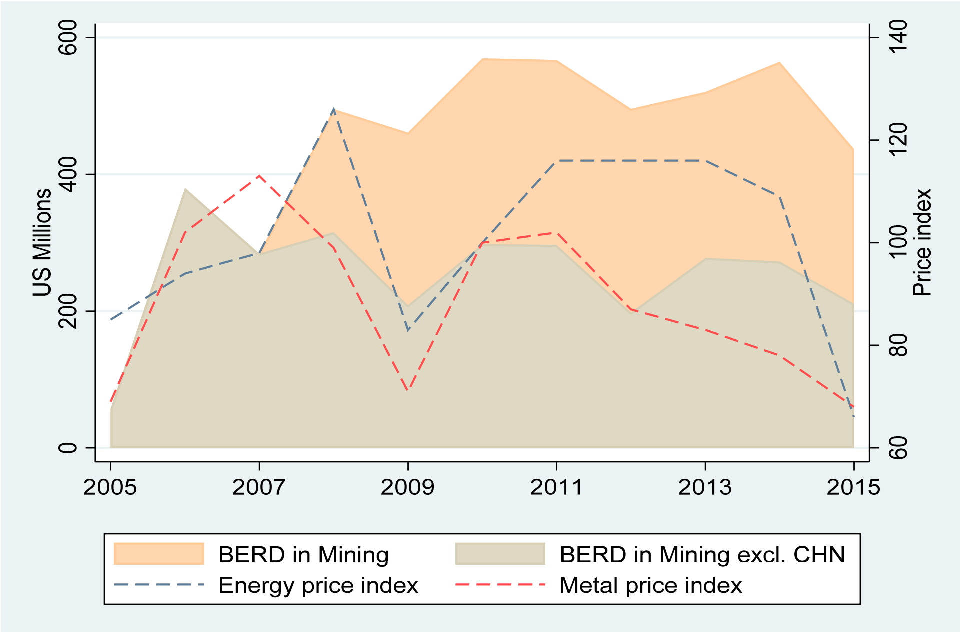

Figure 3. Business R&D figures for the mining sector (USD millions).
Source: Authors' elaboration with OECD and World Bank Pink Sheet data on annual price indices for energy and metals.
Note: BERD: Business Research and Development. Energy price added to reflect coal.

Consistent with our expectation, Figure 4 illustrates the number of patents from suppliers and mining firms for exploration. This figure suggests that the increase in the number of patents (one of the indicators of innovation) is closely related to the increase in the price of metal. It is important to notice that a recent econometric study using the same dataset for patents found that, on average, exploration patents were particularly sensitive to price variation (Valacchi et al., 2019), which is in line with the high pro-cyclicality features pointed out earlier.

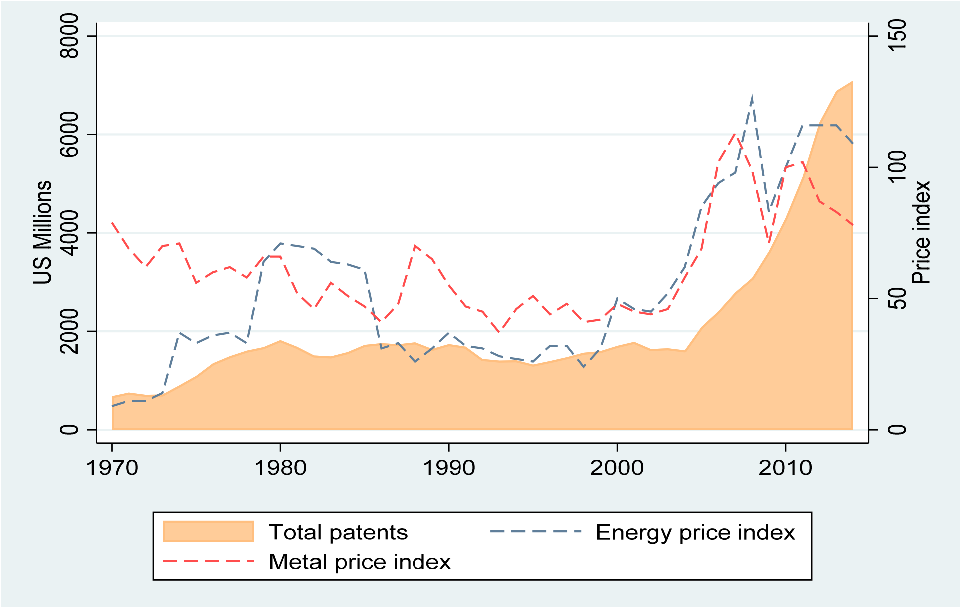

Figure 4. Exploration patents (by family application ID) by METS, mining firms, and mineral commodity price indices (2010 = 100).
Source: Authors' elaboration with OECD data and the World Bank Pink Sheet data on annual price indices for energy and metals
Note: Energy price index are added to reflect METS working for oil, coal, and gas industry.

The evidence discussed above supports our arguments presented in H(1): mining firms increase exploration activity to expand mineral production when mineral prices are on the rise, as they hope to maximise their profits.

4.2 Relationship (linkages) with suppliers (METS)

(1) Patenting activities by suppliers (METS) in contrast to mining firms

The evidence on patenting illustrates yet another trend that concerns mining firms' changing relationship with METS. This trend is characterised by strategic decentralisation (open innovation[7]) and enhancing collaboration in some specific sectors (i.e., large-scale capital equipment). Table 2 presents trends of patenting in mining with more disaggregated data by type of firm, based on data from the World Intellectual Property Organization (WIPO). Firstly, the periods were divided into pre-boom (1970 to 1995) and post-boom (1996 to 2015). Looking at the absolute number of patents shows that specialised suppliers, or METS, acquired more patents than mining firms. During the

[7] Open innovation uses externally generated ideas, often by startups, to solve problems associated with productivity of firms instead of traditional in-house R&D.

post-boom period (from 1996 to 2015), almost 70% of patenting activities in mining firms were concentrated in the exploration sub-sector. This share is double that of the pre-boom period (from 1970 to 1995). While METS have also increased exploration (from 17% to 25%), their patenting remains less concentrated on exploration activities and is spread across the mining sub-sectors. The number of patents is significantly higher in METS than in mining firms in both pre- and post-boom periods except for the sub-categories of exploration and blasting, which also concerns the exploration phase.

Table 2. Category of patent filings according to firm type (1970–2015)

	Automation.	Blasting	Environment	Exploration	Metallurgy	Mining	Processing	Refining	Transport	Total
1970–1995										
METS	19	55	1,966	3,406	329	**6,125**	433	5,803	1,526	19,662
	0.1%	0.3%	10.0%	17.3%	1.7%	**31.2%**	2.2%	29.5%	7.8%	100.0%
Mining	3	73	1,368	**3,729**	116	1,126	559	3,720	159	10,853
	0.0%	0.7%	12.6%	**34.4%**	1.1%	10.4%	5.2%	34.3%	1.5%	100.0%
Total	22	128	3,334	7,135	445	7,251	992	9,523	1,685	30,515
	0.1%	0.4%	10.9%	23.4%	1.5%	23.8%	3.3%	31.2%	5.5%	100.0%
1996–2015										
METS	62	452	5,616	13,316	334	**14,845**	1,910	10,075	6,124	52,734
	0.1%	0.9%	10.7%	25.3%	0.6%	**28.2%**	3.6%	19.1%	11.6%	100.0%
Mining	17	482	3,716	**28,254**	70	4,174	773	4,443	467	42,396
	0.0%	1.1%	8.8%	**66.6%**	0.2%	9.9%	1.8%	10.5%	1.1%	100.0%
Total	79	934	9,332	41,570	404	19,01 9	2,683	14,518	6,591	95,130
	0.1%	1.0%	9.8%	43.7%	0.4%	20.0%	2.8%	15.3%	6.9%	100.0%

Source: Authors' elaboration with WIPO data

The patent data demonstrates that there is a concentration of mining firms in the exploration sub-sector, confirming the arguments presented in H(1). The flipside of this implies the reliance of mining firms on METS for innovation in other subsectors. This partially confirms our arguments in H(2).

(2) The increasing importance of linkages with innovation by suppliers (METS)

According to the Pavitt (1984) taxonomy of innovation, the mining sector closely resembles the supplier-dominated innovation category. This means that mining firms are the users of innovation provided by suppliers. As explained earlier, because their product, a commodity (mineral), is exogenously priced, mining firms are, in general, discourage to innovate by themselves but encouraged to maximise profits through cost reduction through using innovative suppliers. .

To measure degree of third party innovation adopted by the mining industry (i.e., the contribution of innovation by suppliers to the mining industry), this study analysed input-output data at backward linkages. Backward linkages reflect the share of purchases that originate from other sectors, making it possible to trace the in-country contributions of the value generated in the final product. For instance, the share of purchases that are necessary from sector *i* to satisfy the demand of sector *j*. In other words, backward linkages include how much of sector *i* is necessary to produce more in sector *j* (unless specified otherwise). These measures have some limitations because this can include non-innovative inputs. However, the composition of the sectors to which mining sectors are connected are primarily modern sectors, or are linked to the acquisition of new inputs[8] (Calzada Olvera & Foster-McGregor, 2018). Hence, the distortion is expected to be minor.

Empirical studies at country level have shown a decrease (in various degrees) in backward linkages to supplier industries in major mining exporters, such as Australia, Chile, Canada, Brazil, and Russia. Moreover, these results echo other studies that emphasise the weak supplier development in mining countries such as Brazil (Figueiredo & Piana, 2016, 2017) and Canada (Stanford, 2019).

This downward trend of backward linkages in the 2000s can be observed in Figure 5. Using the World Input-Output Database (WIOD) (deflated at the sectorial level to account for price effects), the trajectory for major mining countries' backward linkages[9], that is, Australia, Brazil, Canada, China, Indonesia, Norway, Mexico, Russia, and the US has been rather negative.

[8] These are concentrated on the wholesale and retail trade, repairs, R&D and other business activities, transport, storage, and financial intermediation (Calzada Olvera & Foster-McGregor, 2018)

[9] These were calculated using standard input-output approaches. For details, see Miller & Blair, 2009.

Figure 5. Average value of backward linkages in the mining sector (Inc. imports & domestic purchases) based on samples from 120 countries[10].

Notes: Countries include major mining countries: Australia, Brazil, Canada, China, Indonesia, Norway, Mexico, Russia, and the USA. Source: Authors' elaboration with WIOD data

Furthermore, the negative effect that prices have on linkage formation is statistically significant based on a panel model estimation for more than 120 countries during the 1975–2015 panel (Calzada Olvera & Foster-McGregor, 2019). This relationship remained negative even after controlling for institutional quality. Figure 6 illustrates the negative correlation between linkages and commodity prices, seemingly akin to the negative correlation that has been described with regards to productivity.

[10] An example of how to interpret the backward values: the average value of backward linkages in 2009 was slightly below 1.5 USD. For every extra dollar of mining output, the mining industry, on average, acquired 1.5 USD of inputs from the supplier sectors in that year.

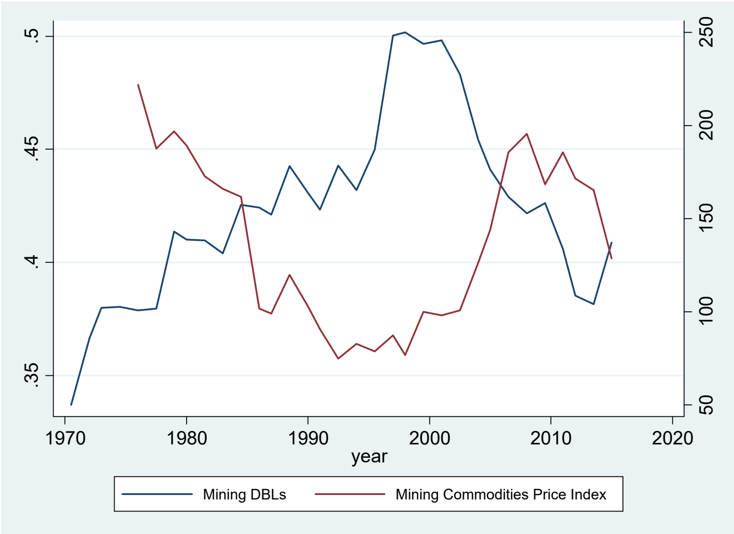

Figure 6. Average mining backward linkages and the mining commodity price index from 1975–2015.
Note: DBL refers to direct backward linkages. The price index is calculated at the country level.
Source: Calzada Olvera & Foster-McGregor, 2019.

The above evidence confirms the arguments that we made in H(2). Backward linkages in the mining sector increase in a counter-cyclical manner with respect to commodity prices, indicating that reliance on suppliers, or METS, would increase when commodity prices decrease. Regarding the reaction of suppliers' services and products to commodity price fluctuations, Chile presents an insightful example. When commodity prices were high during the period between 2003 and 2011, the Chilean mining sector not only experienced a reduced number of suppliers, but supplier-induced innovations in key sectors (transport, commerce, R&D, and financial services) also decreased. Production expansion was realised through the intensified use of energy, labour, and capital in order to make the most out of the price cycle opportunity (Castaño, Lufin, & Atienza, 2019). This trend, however, was reversed when the mineral commodity prices fell. Castaño et al. (2019) further confirm the hypothesis of counter-cyclical trends of reliance on suppliers as mineral commodity prices decline. The World Class Suppliers Program in Chile, a program aimed at fostering innovative suppliers along the value chain, was launched in 2009 right after the sharp decline of copper prices that followed the global financial crisis in 2008 (Urzua, 2012; Urzua et al., 2016). The imminent need to maintain profits (or reduce losses, at least) through the reduction of production costs, has pushed mining firms to look for innovative suppliers.

The above evidence supports the argument that we put forward in H(2). Mining firms increase their linkage with suppliers when mineral prices decline so that cost-reducing innovations, such as customisation and the introduction of digital technologies, are materialised by suppliers to maximise profits. However, this perspective may not be generalised across all countries. Linkage formation in recent years in several Asian countries does not point to a clear counter-cyclical response, as is the case in Latin American countries (Calzada Olvera & Foster-McGregor, 2019). However, on average, empirical evidence supports the idea that technological improvements induced by suppliers (counterintuitively) have been negatively correlated to higher prices. There are reasons to believe that more advanced economies such as Australia, Canada, or the US are more prone to developing mining innovations. However, because productivity and linkages have dwindled by various degrees during the super commodity cycle, this indicates that corporate behaviour in the mining sector (which is largely determined by the profit structure) is undergoing an inherent challenge that has been overlooked by policymakers when targeting to foster linkages in the natural resource sector (mainly in the mining sector).

The empirical study on the cyclicality of prices on patents by Valacchi et al. (2019) finds no evidence of counter-cyclical innovation. The study nonetheless does not rule out the possibility of counter-cyclical innovations happening at the same time as pro-cyclical innovations. What Valacchi et al. (2019) suggest does not necessarily contradict our conclusion regarding innovation since we focus on supplier-induced innovations, which refer to their adoption and is not necessarily related to patenting activities.

5. Conclusion

Emerging literature in this field has claimed that natural resource-based activities, including those within the extractive industry, are no longer a curse. The literature states that the mining sector has the potential to be an innovative sector and to stimulate innovation in other sectors through the emergence and development of specialised suppliers. However, current innovation policies and initiatives may not suffice to spur innovation with the breadth and depth that is needed to tackle current challenges in the industry, such as degrading ore grades, and more importantly, to reap economy-wide benefits through the development of a strong base of innovative suppliers making full use of digital technologies.

This study outlined the characteristics of innovation in the mining sector and illustrated innovation potential and challenges for development in the present-day context. It demonstrated that the innovation processes and supplier development (linkages) within the mining sector are strongly influenced by commodity prices. It illustrated, firstly, that the investment in this sector is pro-cyclical to commodity prices, which are set exogenously by market forces. Secondly, it identified that a large proportion of investment is dedicated to exploration, which functions as R&D in the mining sector. Moreover, the R&D investment, though modest in quantity, also shifts in a pro-cyclical manner to commodity prices. Thirdly, patent data revealed that the METS innovate more than the mining firms, partially confirming that the mining sector follows supplier-dominant innovation (Pavitt, 1984). Fourthly, the concentration in patent areas illustrated the strategic choices taken by the mining firms concentrate their efforts in exploration, and the METS in the rest of the activities, and consequently implying enhanced collaboration between the two. The reliance of the mining firms on METS was confirmed by the input-output data. Furthermore, the use of METS by the mining firms demonstrated a counter-cyclical relationship to commodity prices, suggesting that backward linkages extend further when commodity price declines. The above evidence rejects the long-standing notion of the mining sector operating as an enclave, without much innovation, but rather shows the sector as having complex linkages owing to sectoral characteristics. This means that the mining sector can play a critical role in development, if local suppliers are effectively involved in the productive process.

Nevertheless, the opportunities for suppliers may not be evenly spread across the board. In fact, the majority of patenting in this sector is currently happening in just a few countries, and the upgrading of technological capability still poses a great challenge in some resource-rich countries in developmental stages. Even if suppliers manage to provide innovative solutions to the mining industry, the adoption of these solutions is tainted by the profit-maximising behaviour of the majors whereby high commodity prices put off the adoption of technological solutions and other good practices. This has been more pronounced in developing regions like Latin America than in advanced economies due to factors such as hierarchical relationships along the value chain. However, in advanced countries such as the US, which is a leader in mining-related innovation, productivity in mining sectors has consistently dropped as prices have grown. This suggests that innovation in the mining industry is not just on the supply side but also on the demand side.

The findings on innovation process in mining sector propose two important perspectives to discuss possible policy options. From an industry perspective, rectify the ad hoc approach towards innovation (where short-term gains are prioritised) is necessary to overcome productivity losses. Furthermore, addressing societal challenges such as environmental issues through involving local and regional suppliers into global value chains are critical in order to gain a social license to operate and to enable sustainable mining operations. From a development perspective, it became clear that the fluctuation in mineral commodity prices not only influence economic stability at macro level but also industrial activities at micro level, such as innovation process and linkage formation involving suppliers. Furthering the understanding of how to diversify and smooth-out the demand for mining suppliers' products and services as commodity prices change is crucial to put forward in policy-making discussions. Moreover, how the introduction of digital technologies may change the innovation process in the mining sector remains to be explored.

This paper brought together existing evidence to illustrate the generic characteristics of innovation processes in the mining sector - a sector often misunderstood in development economics and understudied from an innovation perspective. There are some limitations in how much this picture can be applicable to the diverse realities of resource rich countries. Firstly, this paper does not imply that granular observation can be ignored in formulating policy. In fact, the data on patents and R&D investment shows diversity in concentration of knowledge activities among the resource rich countries. This disparity in capability creates differences in how the sector evolves, particularly with regards to the adoption of digital technologies. Secondly, the analysis in this paper relied on R&D and patenting data to evaluate the innovation process in the mining sector. Although these indicators are commonly used to study other sectors, the mining sector's knowledge that contributes to productivity owes much to local specific knowledge that largely remains tacit and not expressed in conventional indicators; thus, this study may not have drawn a full picture of the innovation process in mining.

Finally, a deeper understanding of innovation processes in this sector is crucial for improving the policy effectiveness aimed at increasing the contribution of natural resources toward a more equitable and sustainable development. Further research is needed to examine the validity of the generic characteristics of innovation processes in mining, taking account the transformation of technological and socio-economic aspects.

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