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Title

Innovation and Technological Change in the Mining Industry and Development

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Declaration

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Dedication

To my parents

To my uncle Giancarlo

Abstract

This thesis investigates whether and to what extent innovation and technological change in the mining sector may represent a factor that triggers natural resource-based economic development. Natural resource specialisation tends to favour, and is hence associated with, the emergence of structural weaknesses that may hinder economic development. We suggest that the removal of two major and intertwined structural weaknesses associated with natural resources production, i.e. the lack of innovation in the mining sector and the lack of diversification of productive activities in developing resource-abundant countries can be a successful strategy to pursue natural resource-based development. It is worth stressing that specialisation can co-exist with some degree of diversification. In fact, a country can specialise in the products in which it has a comparative advantage, but also pursue new development opportunities by investing in new promising, higher value-added activities, diversifying into new industries, and extending the range of industries it specialises in.

This thesis addresses four major open questions regarding the links between specialisation in mining industries and development: to what extent being specialised in natural resources is associated with innovation and learning opportunities? Is there path dependence in terms of technologies, regions and firms involved in innovative activities in mining? To what extent are suppliers to mining companies innovative and thus able to establish productivity enhancing linkages with mining companies? To what extent is carrying out mining innovation activities convenient and, hence, profitable for individual companies? The general introduction of this thesis (i.e. Chapter 1) provides the framework for the above research questions.

Chapter 2 examines specialisation patterns in the Latin American mining sector, in terms of exports of mining products, of its exports of mining equipment, and of its production of mining technologies (i.e. innovation). Results suggest that Latin American countries are specialised in the extraction and export of mining products (i.e. minerals), and de-specialised in the production of mining equipment and of mining technology, while they heavily rely on imports of equipment and technology. We also find that the mining innovation taking place in Latin America is of relatively low quality. Considering that innovation in the mining sector is supplier-dominated, the weak technological specialisation of Latin American countries in the mining sector reflects mainly the low innovation capacity of local suppliers of inputs, especially machinery, to mining companies, in comparison with the global average.

Chapter 3 studies technological change in the mining industry at the global level between 1970 and 2015 using patent citation networks. The analysis is further undertaken at the "sub-trajectory" level, by considering nine mining-related technological fields, i.e. sub-networks that represent the 9 technological sub-trajectories. Consistent with previous literature focused on other technological domains, we find that innovation patterns are "technology bounded" in the mining sector, i.e. they are largely shaped by patenting activities carried out in a very limited range of mining technological fields, even though we detect a shift from exploration to environmental mining technologies (emergence of a new technological paradigm). In addition, we examine two aspects of technical change that have been largely disregarded in extant research: the geographical patterns of inventive activities and the role of key applicants in such patterns. We show that core mining patents and leading inventors involved originate almost exclusively from the US, so that trajectories appear to be heavily geographically bounded, revealing that developing resource-rich countries lag behind the technological frontier in mining. Moreover, only a few applicant

firms are responsible for most inventive activities (oligopolistic structure), hence characterizing trajectories as "applicant bounded". Similar results and implications are observed at the level of sub-trajectories, although with few exceptions. Specifically, we find that the Mine operation, Processing and Transport sub-trajectories are the less applicant bounded and, consequently, the less geographically bounded sub-trajectories. This means that a relatively greater number of countries and players (firms) participates to the creation (and diffusion) of knowledge related to these specific mining technologies.

Given the importance of innovation and technical change for natural resource-based development as shown in the previous chapters of this thesis, Chapter 4 examines how the profitability of firms engaged in mining innovation is affected by their portfolios of patents. Combining WIPO data on the patenting activities of over 245,000 firms with specific reference to nine mining technologies for the period 1970-2015 with Orbis data on these firms' profitability over the period 2010-2018, we find that mining companies' innovative activities have on average a negative effect on their profitability, presumably reflecting the high costs of innovation in this field, the relatively narrow range of application opportunities for most new mining technologies, and a conservative attitude of firms in most segments of the mining value chain. Innovation in blasting and metallurgy technologies is a relevant exception to this rule, as patenting in this field appears to have a strong and significantly positive effect on firms' profits. This may relate to the nature of such technologies which are both cost-cutting and applicable in a variety of different contexts within and across the boundaries of the mining industry, hence yielding higher profits. Conversely, environmental technologies have a negative impact on profitability possibly because they are more sector-specific and they compel firms to bear compliance costs due to stricter environmental regulations at the national level. We also find that being technologically diversified in terms of innovation activities across different stages of the mining value chain negatively affects the companies' profits, potentially indicating that it is less costly (and more profitable) to develop mining innovations that are related to the firms' core technological competencies.

The analysis conducted in this thesis highlights the potential tensions between country - and industry - level development opportunities that are associated with innovation and with broader specialisation patterns, going beyond mining industry alone; and firm level propensity to adopt conservative, low innovation and low diversification strategies, especially in terms of the range of competencies accumulated, given the nature of technologies at stake and of appropriability conditions. From this perspective relatively underdeveloped, resource abundant economies may be bound not to escape the poverty trap, unless innovation oriented public policies are undertaken at the national and supra-national levels to overcome the low private incentive to innovate.

Sommario

Questa tesi studia se e in quale misura l'innovazione e il cambiamento tecnologico nel settore minerario potrebbero rappresentare un fattore che innesca uno sviluppo economico basato sulle risorse naturali. La specializzazione nelle risorse naturali tende a favorire l'emergere di debolezze strutturali che potrebbero impedire lo sviluppo economico. Sosteniamo che la rimozione di due rilevanti e collegate debolezze strutturali associate alla produzione di risorse naturali, cioè la mancanza di innovazione nel settore minerario e la mancanza di diversificazione delle attività produttive in Paesi del Sud del mondo ricchi di risorse naturali, possa essere una strategia di successo per perseguire uno sviluppo basato sulle risorse naturali. E' bene sottolineare che la specializzazione può coesistere con qualche grado di diversificazione. Infatti, un Paese può specializzarsi nei prodotti per i quali ha un vantaggio comparativo, ma anche perseguire nuove opportunità di sviluppo investendo in attività nuove, promettenti e a più elevato valore aggiunto, diversificando in nuovi settori, ed ampliando la gamma di settori nei quali si specializza.

Questa tesi affronta quattro principali domande aperte riguardo i collegamenti tra specializzazione nei settori minerari e sviluppo: in quale misura essere specializzati in risorse naturali si associa a opportunità di innovazione e apprendimento? C'è "dipendenza dal percorso" ("path dependence") in termini di tecnologie, regioni geografiche e imprese coinvolte in attività d'innovazione nel minerario? In quale misura i fornitori di imprese minerarie sono innovativi e quindi in grado di stabilire "linkages" che migliorino la produttività con imprese minerarie? In che misura svolgere attività d'innovazione nel settore minerario è conveniente e, quindi, profittevole per le singole imprese? Il capitolo introduttivo (ovvero il Capitolo 1) fornisce un inquadramento generale per l'analisi successiva e discute le domande di ricerca elencate sopra, sulla cui base si sviluppa il prosieguo della tesi.

Il Capitolo 2 esamina modelli di specializzazione nel settore minerario Latino-americano, in termini di esportazioni di prodotti minerari, di esportazioni di attrezzature minerarie, e di produzione di tecnologie minerarie (cioè innovazione). I risultati suggeriscono che i Paesi Latino-americani sono specializzati nell'estrazione e nell'esportazione di prodotti minerari (ovvero minerali), e de-specializzati nella produzione di attrezzature minerarie e di tecnologia mineraria, mentre fanno decisamente affidamento sulle importazioni di attrezzature e tecnologia. Inoltre, troviamo che l'innovazione mineraria che ha luogo in America Latina è di qualità relativamente bassa. Considerando che l'innovazione nel settore minerario è dominata dai fornitori, la debole specializzazione tecnologica dei Paesi Latino-americani nel settore minerario riflette soprattutto la relativamente bassa capacità innovativa dei fornitori locali di materie prime, specialmente macchinari, di imprese minerarie.

Il Capitolo 3 studia il cambiamento tecnologico nell'industria mineraria a livello globale tra il 1970 e il 2015 utilizzando "reti" (networks) di citazioni di brevetti. L'analisi è ulteriormente sviluppata a livello di "sotto-traiettoria", considerando nove campi tecnologici legati al minerario, cioè "sotto-reti" (sub-networks) che rappresentano le nove sotto-traiettorie tecnologiche. In linea con letteratura precedente focalizzata su altri domini tecnologici, troviamo che i modelli di innovazione sono "vincolati tecnologicamente" ("Technologically bounded") nel settore minerario, cioè sono ampiamente caratterizzati da attività di brevettazione svolta in una limitata gamma di campi tecnologici minerari, anche se rileviamo un passaggio da tecnologie minerarie di esplorazione a tecnologie minerarie ambientali (nascita di un nuovo paradigma tecnologico). Inoltre, esaminiamo due aspetti del cambiamento tecnologico che sono stati ampiamente trascurati dalle ricerche esistenti: i modelli geografici delle attività

inventive e il ruolo delle imprese chiave in tali modelli. Mostriamo che i brevetti minerari fondamentali e i principali inventori coinvolti provengono quasi esclusivamente dagli Stati Uniti, di conseguenza le traiettorie sono pesantemente "vincolate geograficamente" ("Geographically bounded"); ne deriva che i Paesi in via di sviluppo e ricchi di risorse naturali si trovano indietro rispetto alla frontiera tecnologica nel minerario. Peraltro, soltanto poche imprese richiedenti (i brevetti minerari) sono responsabili della maggior parte delle attività inventive (struttura oligopolistica), caratterizzando le traiettorie come "vincolate a livello delle imprese brevettatrici" ("Applicant bounded"). Simili risultati e implicazioni vengono osservate a livello di sotto-traiettorie, sebbene con poche eccezioni. Specificatamente, troviamo che le sotto-traiettorie "Mine operation", "Processing" e "Transport" sono le meno limitate a livello d'imprese che le caratterizzano e, conseguentemente, sono le sotto-traiettorie meno limitate geograficamente. Questo comporta anche che più Paesi e più attori (imprese) partecipano alla creazione (e diffusione) di conoscenza in questi ambiti del settore minerario, anche se le imprese statunitensi hanno comunque un ruolo fondamentale e spesso dominante.

Data l'importanza dell'innovazione e del cambiamento tecnologico per uno sviluppo basato sulle risorse naturali come mostrato nei capitoli precedenti di questa tesi, il Capitolo 4 esamina come la profittabilità delle imprese impegnate in attività di innovazione mineraria siano influenzate dai loro portafogli di brevetti. Combinando dati WIPO sulle attività di brevettazione di oltre 245000 imprese con specifico riferimento a nove tecnologie minerarie per il periodo 1970-2015 con dati ORBIS sulla profittabilità di queste imprese nel periodo 2010-2018, troviamo che le attività innovative in campo minerario delle imprese hanno in media un effetto negativo sulla loro profittabilità, presumibilmente per via degli elevati costi d'innovazione in questo campo, le relativamente ristrette opportunità di applicazione nel caso della maggior parte delle nuove tecnologie minerarie, e un approccio conservativo delle imprese nella maggior parte dei segmenti della catena del valore mineraria. L'innovazione nelle tecnologie degli esplosivi e della metallurgia rappresenta un'eccezione rilevante a questa regola; in effetti, brevettare in questi ambiti comporta un impatto forte e significativo sui profitti delle imprese. Questo può avere a che fare con la natura delle tecnologie in questione, le quali sono mirate a ridurre i costi e sono applicabili a una varietà di contesti differenti all'interno e al di là dei confini dell'industria mineraria, permettendo di produrre profitti più elevati. Al contrario, le tecnologie ambientali in campo minerario hanno un impatto negativo sulla profittabilità, probabilmente perché sono più specifiche al settore e perché obbligano le imprese a sostenere costi di conformità legati a regolamentazioni ambientali sempre più stringenti a livello nazionale. Troviamo anche che essere diversificati tecnologicamente in termini di attività innovative lungo stadi differenti della catena del valore mineraria influenza negativamente i profitti delle imprese, indicando potenzialmente che è meno costoso (e più profittevole) sviluppare innovazioni minerarie che sono legate alle competenze tecnologiche chiave delle imprese.

L'analisi condotta in questa tesi evidenzia le potenziali tensioni tra opportunità di sviluppo a livello delle industrie e dei Paesi che sono associate all'innovazione e a modelli di specializzazione più ampi, andando oltre il solo settore minerario; e la propensione a livello d'impresa ad adottare strategie conservative, caratterizzate da bassa innovazione e bassa diversificazione, specie per quanto riguarda la varietà di competenze sviluppate, data la natura delle tecnologie in questione e delle condizioni di appropriabilità. Da questa prospettiva di ricerca deriva che le economie ricche di risorse naturali potrebbero essere destinate a non uscire dalla trappola della povertà, a meno che vengano adottate politiche pubbliche orientate all’innovazione a livello nazionale e sovra-nazionale con lo scopo di superare il basso incentivo privato ad innovare.

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Chapter 1

Challenges of the Mining Industry: Introduction and Key Research Questions[◆]

1.1 The importance of mining for the world economy and the major open questions

Products of the mining industry are an essential part of our lives. We need them to satisfy our everyday needs. Without them industrial production would soon come to a halt (Mikesell and Whitney, 1987). Natural resources are the primary inputs to most production processes and they supply the energy for transport, light and heat around the world (Andersen et al., 2015).

Mining and other associated activities are a significant part of the global economy. The value of global mine production has been estimated at around USD 1.3 trillion in 2014, corresponding to about 1.6% of world GDP (Lof and Ericsson, 2016). In 2015, mining-related commodities represented approximately two percent of the world's total trade (UN COMTRADE, 2016). The direct and indirect impact of mining industries on economic growth is even more relevant than their weight in total GDP and trade.

Andersen et al. (2015) argue that the way the world manages natural resources will be a crucial factor in determining the scope for sustainable development in the world economy. In fact, as the world is confronted with climate change, natural resource management becomes an urgent issue to address. The growing worldwide population, together with rising living standards, has increased the demand for minerals. Typically, the mining industry meets increasing demand in the short-term by optimizing operations in existing mining sites with decreasing returns. In the long-term, mining companies search for new mining sites that meet the demand requirements. In addition, the mining industry faces continuous operational challenges to fulfil the increasing sustainability and social requirements demanded by society (Valacchi, Raffo, Daly and Humphreys, 2019). Innovation is a key instrument to address all these challenges (see e.g. Daly, Valacchi and Raffo, 2019; Perez, 2015).

The "mining sector" is usually identified with the branch of manufacture and trade based on the extraction of ores, fossil fuels, minerals, stone, clay, gravel and similar commodities. It has important interdependencies and connections with upstream specialized machinery industries, and downstream refinement and commercialization activities[1]. As such, this set of industries greatly contributes to the

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I thank the participants at the Phd Seminar Sessions organized by the University of Urbino (Urbino, Italy, May 28-29th 2019) for their insightful comments. This chapter also benefitted from discussion with Beatriz Calzada Olvera, Andrea Coveri, Giovanni Dosi, Giovanni Marin, Carlo Pietrobelli and Julio Raffo.

[1] This thesis is based on this broad definition of the mining industry, including all the relevant industry categories according to the Standard Industry Classification codes (1.1.2.3.5.1 Coal Mining Industry; 1.1.2.3.5.2 Metal Mining Industry; 1.1.2.3.5.3 Nonmetallic Mineral Mining Industry; 1.1.2.3.5.4 Oil and Gas Extraction Industry). Most of the analyses carried out in this thesis consider the mining industry from an innovation perspective following extant literature (see e.g. Calzada Olvera and Iizuka, 2020; Daly, Valacchi and Raffo, 2019; Fernandez, 2021; Humphreys, 2019; Iizuka, Pietrobelli and Vargas, 2019). Specifically, we analyse technologies related to metallic and non-metallic minerals and coal, excluding other fossil fuels

economies of emerging countries, in particular Latin America and Sub-Saharan Africa (Iizuka, Pietrobelli and Vargas, 2019). The continued importance of mining resources is likely to persist, as reserves for key minerals are mainly present in emerging countries, and notably in Latin America (US Geological Survey, 2018). The commodity bonanza that many emerging economies experienced during the last decade renewed the interest of many scholars in the potential of natural resources as a platform for economic development, especially in resource-rich middle-income countries (Calzada Olvera and Foster-McGregor, 2018). This strategy has been especially appealing for the Latin America region whose revealed international competitive advantage lies mainly on natural resources, but also includes scientific knowledge and skilled labour (Lin and Treichel, 2012). Despite the described importance of the mining industry at the global level, specialisation in the mining sector may be subject to some open key issues, mostly linked to innovation and development. It is worth noting that we often see that countries rich in natural resources become highly specialized in, and dependent on, production and export related to such resources (WTO, 2010). However, it may be problematic for countries to be overly specialised in natural resources. First, being economically dependent on exporting only a few products makes countries vulnerable to changes in demand for these products. Second, economic development is intimately associated with diversification of the economy (Hidalgo and Hausmann, 2009). Countries should therefore add diverse productive activities to their resource activities. Third, several researchers state that natural resource dependence may directly inhibit growth and development (Andersen et al., 2015).

We summarise four main issues regarding the mining industry that are addressed by this thesis from different perspectives in the following three chapters. The first key issue that this thesis addresses is the following: to what extent being specialised in natural resources production may be an opportunity of innovation and learning, and thus of economic development? Reacting to the resource curse literature, an important body of historical studies has argued that natural resources have always been the locus of learning, innovation and linkages, and that the relevant question is not so much whether or not resources are bad for growth and development and why, but under which conditions they might contribute to development and growth (see for instance Smith, 2007; Andersen, 2012; Ville and Wicken, 2013; Marin, Navas-Aleman and Perez, 2015). A recent stream of literature, i.e. the Global Value Chain (GVC) approach has suggested that natural resource-based development is achievable if developing resource-abundant countries (e.g. Latin America) enhance innovation in the natural resources sector (Marin, Navas-Aleman and Perez, 2015; Perez, 2015). In fact, innovation helps to generate spillovers and linkages between the extractive industry and other sectors such as manufacturing and the services sector, increasing the current and potential range of industries into which a country is specialized in terms of production (see for example the experience of Australia and Norway) (Andersen et al., 2015; Bjornland and Thorsrud, 2015). In this context, our main argument is that specialisation in mining production must be accompanied by specialisation in mining innovation, to have technological and economic development opportunities especially in developing resource-abundant countries. We empirically address this issue in Chapter 2 of this thesis for a developing resource-abundant geographical region, i.e. Latin America. We consider sector specialisation as a dynamic concept, suggesting that diversification of productive activities and specialisation are not opposites, because a country may specialise in the products in which it has a comparative advantage, but also develop new specialisations over time thus implying some degree of diversification (Imbs and Wacziarg, 2003; Nomaler and Verspagen, 2021). In fact, Hidalgo and

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different from coal considering that the underlying technologies are quite different one from another. Further information and details on this are provided in the following sections of this introductory chapter and in the other thesis chapters.

Hausmann (2019) find that, related to the concept of dynamic comparative advantage, diversifying into more complex products brings higher development opportunities than adopting an industrialisation strategy mainly based on a single sector. In this manner, a developing resource-rich country may enter a horizon of dynamic competition (built on innovation-based Schumpeterian efficiency (Dosi and Tranchero, 2021) that is better for development than a narrow specialization based on a few productive activities related to natural resources, which have the feature of impoverishing the nation and where competition is only (or mainly) based on price (Cimoli et al., 2006). More precisely, Schumpeterian efficiency is a dynamic concept that pertains technological change and the specialization in sectors that create more technological externalities, have higher technological opportunities and exhibit higher rates of innovation (Dosi and Tranchero, 2021). The paramount importance of technical change in shaping the possibilities of economic growth clarifies why Schumpeterian adjustments are fundamental: specialization in the most innovative sectors dominates over the short-term gains induced by Ricardian comparative advantages[2] (Dosi, Riccio and Virgillito, 2021).

The second key issue has to do with the following research question: is there path dependence (technology boundedness) regarding mining innovation activities on the international technological frontier? A general property of technical change is that innovation and learning are local and cumulative (David, 1985; Arthur, 1994; Cimoli and Dosi, 1995). Local means that the exploration and development of new techniques is likely to occur in the neighbourhood of the techniques already in use. Cumulative means that current technological development often builds upon past experiences of production and innovation, and it proceeds via sequences of specific problem-solving junctures (Vincenti, 1990). Clearly, this goes very well with the ideas of paradigmatic knowledge and the ensuing technological trajectories (Dosi, 1982; Martinelli, 2012). Relatedly, the above research question is based on the possible existence of path dependencies characterising mining innovation patterns, whereby the interaction between micro decisions and some form of learning or some externalities produces irreversible technological paths and lock-in effects with respect to technologies which may well be inferior to other notional ones (Nelson, 2008b). In addition, we examine two aspects of technical change that have been largely disregarded in extant research in mining: the geographical patterns of inventive activities and the role of key applicants in such patterns. Path dependence phenomena for the mining industry risk becoming stronger and penalizing developing resource-abundant nations that are not able to produce frontier technologies in the mining field, i.e. mining technologies that are not on technological trajectories that consolidate during time, excluding firms and countries that are not on the main path (main flow of knowledge) of the technological trajectory. This may happen especially whether knowledge related to frontier technologies does not diffuse across these countries (Bell and Pavitt, 1993; Eaton and Kortum, 1999). We use technological trajectories as a tool to identify frontier mining technologies. Furthermore, the process of development and industrialisation are strictly linked to the inter- and intra-national diffusion of "superior" techniques. Relatedly, at any point in time, there is likely to be only one or, at most, very few "best practice" techniques of production which correspond to the technological frontier. In the case of developing economies, the process of industrialisation is thus closely linked with the borrowing,

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[2] In this context, Dosi, Riccio and Virgillito (2021) argue that, for a country, producing "microchips" is not the same as producing "potato chips". Dosi, Riccio and Virgillito (2021) find that, during the phase of globalization, the probability for low-income countries to produce "potato chips" has increased while the transition probability toward the production of "microchips" has been reducing. This suggests that developing resource-abundant countries increase their specialization in natural resources, which is a type of specialization that may impoverish the country especially if strategic and intelligent policies entailing encouraging innovation and diversification are not adopted.

imitation, adaptation of established technologies from more advanced economies. These processes of adoption and adaptation of technologies, in turn, are influenced by the specific capabilities of each economy (Fagerberg and Verspagen, 2021). Moreover, at the micro level, technologies are to a fair extent incorporated in particular institutions, the firms, whose characteristics, decision rules, capabilities and behaviours are fundamental in shaping the rates and directions of technological advance. In this context, chapter 3 of this thesis addresses the following key issue: how wide is the range of mining innovations/geographical regions/firms on the international technological frontier?

The third relevant problem we wish to stress in the case of the mining industry, among others, is the creation of backward and forward linkages (Hirschmann, 1997) has key to natural resource based development. This issue calls for the creation of structural relationships between mining companies and third parties, e.g. suppliers of mining firms that are called Mining Equipment Technology Services (METS) firms (Bravo-Ortega and Munoz, 2015; Figueiredo and Piana, 2016; Scott-Kemmis, 2013). METS firms are crucial for the innovativeness of the mining industry mainly because innovation in the mining industry is supplier-dominated according to the Pavitt taxonomy[3] (Pavitt, 1984). Supplier-dominated industries are mostly traditional sectors (as it is the case inter alia of mining) producing goods whose production technologies are typically developed elsewhere in the economy (Nuvolari and Russo, 2021). The key question here is: to what extent are METS companies innovative and thus able to establish linkages with mining companies? This is a question difficult to disentangle particularly for developing resource-abundant regions, e.g. Latin America where local METS are usually less innovative than at the global level, with weak linkages to mining companies which prefer to rely on foreign suppliers instead (Bravo-Ortega and Munoz, 2015; Calzada Olvera, 2021; Pietrobelli, Marin and Olivari, 2018). Moreover, considering that many METS companies are suppliers of mining equipment and machineries used both in upstream and downstream stages along the mining value chain, it is worth examining whether a developing resource-abundant region such as Latin America is specialised in producing mining equipment, technology and/or whether they are specialised in using (importing) these equipment and machineries. This is a proxy for revealing the strength or weakness of local METS (suppliers), even considering that being specialised in producing mining equipment (i.e. technology) for a region specialised in producing mineral commodities is a means to develop specialization in higher value-added activities within the mining value chain, bringing technological upgrading[4] and thus development opportunities (Kaplan, 2012).

The fourth key issue addressed by this thesis is based on the previous three open questions that fuel the innovation dilemma: to what extent is carrying out innovation activities convenient and thus profitable for companies? The extant literature finds that the relationship between innovation, technological diversification and profitability is differentiated and varies across sectors (Klepper, 1997) and firms (Teece, 1986). Bogliacino and Pianta (2013) argue that answering the question on the impact of innovation on firms' profits sheds light not only on the different patterns of innovation, but also on the understanding of industrial dynamics. Cefis and Ciccarelli (2005) find that innovations have a positive effect on profits after controlling for relevant characteristics at both the sector and firm level. However, it may not always be profitable to carry out innovation activities, and part of the extant literature finds a

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[3] Pavitt (1984) aims to provide taxonomies of sectoral technological patterns on the basis of firms' innovation sources, strategies and user-producer relationships.

[4] It is worth emphasizing that technological upgrading within the mining value chain often means non-mining production and innovation, relying on METS firms.

negative relationship between innovation and profits (see e.g. Cerulli et al., 2021; Grabowski et al., 2002; Hanel and St-Pierre, 2002). The effect of innovation efforts on profitability depends inter alia on the firm's capacity to appropriate the benefits from innovation. Appropriability varies from industry to industry and depends on the effectiveness of instruments of intellectual property protection and strategies used by firm to prevent competitors to imitate their innovations (Hanel and St-Pierre, 2002). In the specific case of the mining industry, innovations are characterised by a low level of appropriability, thus potentially hindering firms' profits (Calzada Olvera, 2021). In addition, innovation in mining has mainly cost-cutting purposes and it is often tricky (and costly) to develop this type of cost-reducing innovation (Iizuka, Pietrobelli and Vargas, 2019; Sanchez and Hartlieb, 2020). This arises the expectation of a potential negative impact of mining innovation on firms' profits especially in the segments of the industry that are characterised by weaker appropriability regimes and by narrower commercialisation opportunities, leading individual firms to underinvest in innovation capacity and hence undermining economy-wide development opportunities[5]. Relatedly, we also examine how technological diversification in terms of nine mining-related technological sub-fields (within the technology field "mining") affects firms[6]' profitability.

1.2 Rationale of the study and scientific relevance

This section provides some conceptual backgrounds related to the four open key issues concerning the mining industry, i.e. the key research questions of this thesis. In particular, Section 2.1 discusses the first key issue on whether and to what extent being specialised in natural resources production may be an opportunity of innovation and learning, and thus of economic development. This is subject matter of Chapter 2 of this thesis. Section 2.2 illustrates the literature behind the second key issue on whether and to what extent technologies, regions and players (firms) are bounded on the international mining technological frontier, an issue that is central in Chapter 3 of this thesis. Section 2.3 describes the third major open question of this thesis, i.e. the importance of METS companies for the mining industry, their paramount role in innovation and linkage creation with mining companies, as a means to provide technological upgrading and catching up along the mining value chain. The role of METS in shaping innovation in the mining industry and in creating development opportunities in resource abundant countries is a recurring theme throughout this thesis and informs the analysis conducted in all its chapters. Section 2.4 digs deeper into the existing literature regarding the fourth key open issue of this thesis, i.e. whether it is convenient (profitable) for firms to carry out mining innovation activities and being technologically diversified in mining-related technologies, paving the way to Chapter 4 of this thesis.

1.2.1 Specialisation in natural resources production, innovation and economic development

In line with much of the resource curse literature, researchers specialised in technology policy and innovation studies have argued that natural resource intensive industries are problematic mainly because they create scarce opportunities for learning and innovation, and because they have few linkages with other sectors of the economy (Andersen et al., 2015). Relatedly, this thesis investigates whether

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[5] The focal point refers to the contrast between individual and collective interests. More precisely, whereas countries can benefit from technological development occurring in the mining industry, individual firms may not experiment immediate economic returns related to mining innovation activities.

[6] We refer to firms that carry out mining innovation activities at the global level. Thus, they are not necessarily mining companies.

specialisation in mining production is accompanied by specialisation in mining innovation in a developing resource-abundant region, i.e. Latin America (see Chapter 2 of this thesis). According to Malerba (2002) and Park and Lee (2006), some industries are more technologically dynamic than others. This is because they can benefit more from advances in knowledge bases, in advances from technology suppliers and from feedbacks of knowledge within the same industry.

A national resource based development strategy is quite risky if not accompanied by substantial efforts to upgrade and diversify both within and beyond the natural resource sector (Pietrobelli and Rabellotti, 2011). Cimoli et al. (2006), for example, argue that the abundance of resources can sustain growth without significant efforts for learning in the short term, but that in the long-run economic rents derived from these resources tend to be eroded. Moreover, in the context of dwindling supplies and the necessity to extract natural resources from more difficult locations, innovation is increasingly necessary as a means of achieving profitable mineral extraction from less favourable locations or from lower quality mines. Such innovation efforts would encompass processes related to exploration, extraction and transportation technologies (Molina, Olivari and Pietrobelli, 2016). In other cases, especially when natural resources are abundant, but labour is scarce, significant technological efforts may be required to boost labour productivity (e.g. the case of Latin America). To summarise, production specialisation without innovation specialisation can lead to a lack of long-run development[7] (Cimoli and Porcile, 2011; Dosi and Tranchero, 2021). When economic rents are purely based on the relative abundance of resources without fostering innovation, the capacities to induce or respond to shocks and changes is reduced, since the country basically lacks the technological capabilities necessary to readapt the production system to changing contexts (Cimoli et al., 2006). Furthermore, in Latin America, firms operating in the natural resources sector have become more closely integrated in to global value chains in which the stimulus to speed up indigenous learning was abandoned in favour of a focus on homogenization of inputs and goods within a hierarchical system of production (ECLAC, 2008). This occurred in parallel with the progressive commoditization of the production of goods and services in the Latin American region. These processes jointly resulted in a disarticulation of local production chains along with the marginalization of small and medium domestic firms. Rationalization based on the more intense use of imported inputs and equipment produced blanks in the production matrix and had negative effects on the levels of employment and heterogeneity (Cimoli and Porcile, 2011).

For centuries, economists have debated the role of economic specialisation and diversification in economic development. On the one hand, traditional trade models suggest that – on an aggregate level – countries benefit from opening to trade and specialising in the production of goods in which they have a comparative advantage, i.e. specialising on "what one does best". By becoming more specialised, the allocation of resources becomes more efficient, allowing for mutual welfare increases (Krugman and Obstfeld, 2006). The Ricardian trade theories (Ricardo, 1817) and the Heckscher-Ohlin model (Leamer, 1995) suggest that countries should produce and export goods, no matter their quality, using the resources that they have in abundance. It is supposed to be cheaper to produce these goods for the countries that adopt this strategy. It is worth stressing that classical and neo-classical trade theories consider natural

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[7] Learning and innovation reshape international competitiveness and allow countries to exploit the opportunities of international trade and growth (Alcorta and Peres, 1998). Furthermore, technological efforts are mediated by the transformation of the production structure. A structural change that promotes sectors that create and diffuse technology allows to capture the opportunities of international demand dynamism (Cimoli et al., 2006; Hausmann, Hwang and Rodrik, 2007).

resources a blessing for economic development. The main difference between classical and neo-classical economists is that the latter do not contemplate technological progress in the production function. On the other hand, it has been argued that the diversification of production and exports can make a country less prone to negative economic shocks. The relevance of economic diversification has been advocated by famous economists such as Nobel laureate Simon Kuznets, who states that a country's economic growth may be defined as a long-term rise in capacity to supply increasingly diverse economic goods to its population (Kuznets, 1971). Policymakers, in particular in low-income countries, are thus faced with contradicting theories about the best path to sustainable economic growth (Kaulich, 2012; Osakwe, 2007). This thesis investigates under which circumstances specialisation in the mining industry is a constraint or rather an opportunity (or a mix of both) for economic development (see Chapter 2 of this thesis).

Large resource endowment (e.g. mining) often turn out to be a comparative dis-advantage in practice according to the Evolutionary economists (Dosi and Tranchero, 2021). The higher the share of goods intensive in natural resources in total exports, the less dynamic will the export structure be, to the extent that the international demand for goods intensive in natural resources grows at lower rates than the demand for industrial goods. This is particularly true for those of medium and high technology, e.g. in Latin America (Cimoli and Porcile, 2011; ECLAC, 2008).

Another natural resource-related issue is whether natural resources may lead to economic growth in the short term and/or in the long period. Alexeev and Conrad (2009) argue that there is little or no evidence that the large endowments of oil or minerals slow long-term economic growth. In fact, Alexeev and Conrad (2009), by focusing on the levels of per capita GDP, found that natural resources enhance long-term growth. However, a large body of literature finds the contrary, arguing that the existence of abundant natural resources can sustain high rates of growth only in the short period (see e.g. Cimoli and Katz, 2003; Dosi and Tranchero, 2021; Sachs and Warner, 2001). In fact, in the long term, this reduces the structural capacities of capturing the opportunities of technological progress and reacting to shocks flexibly (Cimoli et al., 2006; Hidalgo and Hausmann, 2009).

Furthermore, Haraguchi et al. (2017) and Szirmai (2012) argue that specializing in the manufacturing sector has a higher potential for technological progress and it has traditionally absorbed significant quantities of skilled labour, unlike mining activities (Rodrik, 2016; Szirmai and Verspagen, 2015). Moreover, linkages between natural resource production and other sectors have historically been weaker than between manufacturing and the rest of the economy (Greenwald and Stiglitz, 2013). Hirschmann (1977) states that a higher share of technology-intensive sectors gives rise to externalities and increasing returns, spill-over effects which boost growth and allows the transformation of the productive structure towards rents generated by knowledge and learning, rather than by the availability of natural resources (ECLAC, 2010). Nonetheless, Bjornland and Thorsrud (2016) find that in the case of two developed countries, i.e. Australia and Norway a booming resource sector has substantially productivity spillovers on non-resource sectors in the two countries under study, even though the picture is gloomier for Australia considering that there is evidence of a Dutch disease effect with crowding out of non-resource industries.

Recently, although the natural resource price boom taking place between 2003 and 2011 contributed to growth in several Latin American countries and African countries, this has (especially in Africa) failed to translate into the expected employment growth and improvement of socio-economic indicators

(Andersen et al., 2015; UNCTAD, 2013). It must be stressed that there exist differences between types of natural resources production and development: mineral-producing countries perform better than oil-producing countries and non-mineral countries in Africa as measured by indices of human development and governance (Ericsson and Lof, 2019). In addition, the resource boom has had limited structural impact on natural resource rich developing countries, something which may foreshadow an unsustainable growth path for the longer run due to lacking diversification beyond and within the natural resources sector (UNCTAD, 2013).

To the benefit of the national economies, it is important to encourage a process of structural change where the expansion of natural resource intensive industries is associated with processes of learning, innovation and competence building within (at the level of producers), around (at the level of suppliers and users) and beyond (inter-industry spillovers) production activities (Andersen et al., 2015; Marin, Navas-Aleman and Perez, 2015). A central challenge for resource intensive developing countries is, thus, to move towards a more knowledge intensive and innovation-driven mode of producing natural resources.

Nomaler and Verspagen (2021) argue that the acquisition of technological capabilities, both by means of imitation and innovation, provides opportunities for diversification. The theoretical angle also raises questions about the conceptualization of diversification and specialisation of production (export) activities. A part of the (mainstream) literature sees specialisation and diversification as opposites on a scale. While this may have some intuitive appeal, this view is based much more on (casual) empiricism than on theory. From the point of view of Revealed Comparative Advantage (RCA) and the Ricardian trade theory (Ricardo, 1817) that underlies it, diversification increases if the number of products that a country specialises in increases. This makes specialisation rather similar to diversification, rather than its opposite (Imbs and Wacziarg, 2003; Kaulich, 2012; Nomaler and Verspagen, 2021). Regarding natural resources specialisation, Nomaler and Verspagen (2021) find that the countries specialised in natural resources production are the less diversified in their large sample of countries, and that low diversification of productive structure is exclusively associated with low levels of development. It seems that natural resources play a role in inhibiting diversification and thus development. Perez (2015) states that, particularly in the case of developing resource-rich countries, policies should be able to transform static comparative advantages in natural resources into dynamic advantages, fostering diversification of production in knowledge-intensive activities that are horizontally, vertically and laterally related to the natural resources sector each country chooses to develop. An appropriate policy strategy would promote technical change and would entail creating conditions for learning and innovating that would result in new value-adding processes and in more specialized products with higher and more stable prices and markets. This means that the current opportunity opens up the possibility of adding some of the key characteristics of manufacturing to natural resources industries in a process of resource-intensive industrialization.

As a matter of fact, taken in isolation, endowments in resources or capabilities are insufficient. What is crucial to understand in the contemporary context of natural resources is the importance that networks play in development (Marin, Navas-Aleman and Perez, 2015). It is no longer useful to see natural resources as just the extracting or farming activity on its own, but rather to embrace and promote the complete network, from capital goods and other investment requirements through the production and various processing activities, all the way to packaging, distribution and end use (Perez, 2015). Such a network of actors and activities is what has been understood as a system of innovation (Lundvall, 2007). Such a system includes innovative potential at every step in the natural resources process from exploration, research, design and engineering to transportation, marketing and distribution, as well as in the universities and KIBS (Knowledge Intensive Business Services) (Urzua, 2007), supporting each element of the value chain (Andersen et al., 2015; Figueiredo and Piana, 2016; Perez, 2015; Pietrobelli, Marin and Olivari, 2018).

A widespread perception among political scientists and economists is that natural resource-based activities, especially the mining industry, might represent a "curse" for economic development (Auty, 1990; Brunnschweiler and Bulte, 2008; Douglas and Walker, 2017; Sachs and Warner, 1997). This perception has been formed based on researches from international trade, employment and industrial development (Hirschman, 1958; Prebisch, 1950; Sachs and Warner, 1995). For the sake of completeness, there is a branch of (mainstream) literature that finds that the effect of a large endowment of oil and other mineral resources on a country's economic growth has been on balance positive (Alexeev and Conrad, 2009; Davis and Tilton, 2008; Smith, 2015). In particular, Smith (2015) finds that positive GDP effects of natural resources wealth are concentrated in developing countries, with small and insignificant effects when the sample is limited to OECD countries. Conversely, the main message of the Structuralists is that an expansion of natural resource intensive industries is most likely detrimental to development (Singer, 1949). The policy recommendations for developing resource-rich economies have been to move away from natural resources because of a number of different challenges for development. These mainly include macroeconomic challenges, institutional challenges, innovation and industry challenges (Andersen et al., 2015). For instance, concerning macroeconomic challenges, the terms of trade of developing countries specialised in natural resources was deteriorating vis-à-vis the high-income countries specialised in manufacturing. Both Prebisch (1950) and Singer (1950) saw this as a main obstacle to economic development in Latin America.

Hence, the relationship between natural resource specialisation and development can be described as a relatively complex one characterised by a variety of challenges and opportunities, which may well lead to the extreme condition identified as "resource curse" (James, 2015). Besides, being characterised by a resource curse may per se be a highly variegated condition, so that one would better talk about "degree" of resource curse, rather than identifying a single, punctual level of resource curse. Natural resource based specialisation tends to favour, and is hence associated with, the emergence of structural weaknesses that may hinder development (labour market fragilities, financial instability, low quality of institutions, lack of innovation, lack of diversification, and the degree of dependence of an economy on natural resources as captured for instance by the concentration of inward FDI in the extractive sector). Countering these impoverishing effects of natural resource specialisation effects is not an easy task. However, a number of successful experiences exist that highlight that investing in innovation and coupling natural resource specialisation with wider portfolios of specialisations (i.e. diversification) through the attraction of FDIs in different industries may be a way out of the poverty trap (Narula, 2018).

During the 2000s a new literature has emerged challenging the existence of such a curse, putting forward historical examples (see e.g. Wright and Czelusta, 2004), as well as raising a range of issues questioning the empirical soundness of the evidence on which the resource curse was based (Stijns, 2000; Brunnschweiler and Bulte, 2008; Lederman and Maloney, 2016). In particular:

(i) The original studies looking at the resource curse (Sachs and Warner, 1997) are based on cross sections, which cannot capture causal links, e.g. the evolution over time of both institutions and technology (Van der Ploeg and Poelhekke, 2017).

(ii) Natural resource abundance is often confused with natural resource dependence[8] (Brunnschweiler and Bulte, 2008) and when this is disentangled from natural resource rents, the latter can actually have a positive impact on economic growth (Ding and Field, 2005).

(iii) The main problem with natural resource dependent countries is a lack of export diversification rather than something inherent to natural resources (Bontadini and Savona, 2019). In other words, the key issue is not of specializing in natural resources, but of "over-specializing" and "mono-specializing" in the natural resources sector (Hausmann, Hwang and Rodrik, 2007; Hidalgo et al., 2007).

Recently, the role of the mining industry in economic development has been given a renewed attention from an innovation perspective (see e.g. Calzada Olvera and Iizuka, 2020; Katz and Pietrobelli, 2018). Innovation is essential in improving productivity, which would bring about economic growth. However, historically, innovation policies had been designed based on experiences from the 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. The interplay of several characteristics of the mining sector poses challenges in the quest to achieve higher levels of productivity, profitability and economy-wide technological upgrades through innovation (Calzada Olvera and Iizuka, 2020). These are among the reasons why, in this thesis, we investigate innovation patterns and the characteristics of innovation processes in the mining industry as a potential driver of economic development, with a focus on developing-resource rich countries (see, in particular, Chapters 2 and 3 of this thesis). Regarding the impact of mining innovation and mining technological diversification on firms' profitability, see Chapter 4 of this thesis.

To sum up, we suggest that the most severe and intertwined negative factors associated to a (narrow) specialisation in natural resources production may be the lack of innovation in the natural resources sector (Perez, 2015; Perez, 2010) and the lack of diversification of productive activities (Hidalgo and Hausmann, 2009). The latter is a means to reduce the volatility of markets and to increase linkage creation opportunities (Hausmann, Hwang and Rodrik, 2007). Deller and Schreiber (2012) point out that localities that "settle" on being dependent upon a single industry, e.g. mining, and do not seek to diversify from that industry, expose the local economy to unnecessary risks[9]. In fact, specializing in some products will

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[8] Hailu and Kipgen (2017) state that resource abundance refers to resource endowments or stocks, which to a large extent are endogenously determined, while resource dependence refers to the importance of the resource sector to an economy in generating tax revenues, foreign exchange, growth and employment. Thus, resource-dependence becomes applicable once extraction takes place, while being resource abundant does not necessarily imply extraction of the resources. These two terms are used interchangeably in misleading ways when evaluating various resource curse hypotheses. It is worth highlighting that a nation that is resource abundant may not be resource dependent if it diversifies its production structure.

[9] Advanced countries are found to export also products for which they do not possess a comparative advantage, contrarily to what Ricardo (1817) would have predicted. In general, comparative advantage theory is found working only for developing countries, whose export basket is limited to a handful of products. This asymmetry shows the relevance of diversification (Hidalgo and Hausmann, 2009) and its advantage over Ricardian specialization (Tacchella et al., 2013). However, diversification is a luxury only available for countries that possess the necessary productive capabilities (Dosi and Tranchero, 2021).

bring higher growth than specializing in others (Hidalgo et al., 2007). Everything else being the same, countries that specialize in the types of goods that rich countries export are likely to grow faster than countries that specialize in other goods. Rich countries are those that have latched on to "rich-country products", while countries that continue to produce "poor-country" goods (e.g. natural resources) remain poor (Hausmann, Hwang and Rodrik, 2007; Hidalgo and Hausmann, 2009; Bontadini and Savona, 2019).

1.2.2 Innovation patterns on the international mining technological frontier

The mining industry appears to be more prone to innovate through the adoption of technologies developed by a (foreign or local) third-party, hence the historical importance of knowledge intensive suppliers in countries such as Australia, Canada and the US. However, the adoption of technologies is not exempt from risks (Pietrobelli, Marin and Olivari, 2018). For instance, adopting a new technology is only done when the technology has been extensively used in other areas, reducing the perceived risk by mining companies, considering that this technology will be in place for many years (Calzada Olvera, 2021). In this context, and relatedly, we do believe that knowing which regions and players produce frontier technologies in mining, and where and to what extent these frontier mining technologies diffuse across countries, may be relevant for upgrading and technological development in mining especially in developing and emerging countries, with economic development consequences (Fagerberg, Srholec and Verspagen, 2010). This is our second key issue that this thesis addresses. Specifically, in this thesis, we examine how countries differ in terms of innovation patterns in the mining industry (see Chapter 3 of this thesis). In fact, Bell and Pavitt (1993) state that technical change in industry has conventionally been seen as involving two main activities: first, the development and initial commercialization of significant (leading edge) innovations; second, the progressively wider application of these innovations in a process that economists and others have described as "diffusion". The first of these activities is assumed to be heavily concentrated in the developed countries, becoming significant in developing economies only as they approach the international technological frontier. Technology acquired from other countries has been essential in the industrial growth of the developed countries. It was obviously important when economies were catching up from behind the technological frontier, but it remains important for those that are operating close to the frontier. A very large proportion of total international trade in technology, either as disembodied knowledge or as technology embodied in capital goods and engineering services (e.g. mining equipment in our case), takes place between them and the industrializing countries of the developing world (Bell and Pavitt, 1993; Smith and Vivdei, 1992). It is worth stressing that the argument that importing foreign technology and creating it locally are alternative (substitutable) means for generating technical change does not reflect the experience of the developed countries, where technology imports and local technological accumulation have in fact been complementary. In other words, firms have not to choose between imported and local technology as sources of technical change, but they should choose both. This is not the case of the Latin American mining sector, as we show in this thesis. In fact, this developing resource-abundant region is specialised in importing foreign mining equipment and technology, but it is not specialised in creating local mining technology/knowledge, even though we detect a certain level of heterogeneity among Latin American countries. Bell and Pavitt (1993) argue that a pattern of technical change based simply on the adoption (use) of foreign technologies, without local

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production of international frontier technologies, and followed by productivity improvements resulting automatically form experience in production is inadequate to provide concrete development opportunities and to lay the basis for related and higher value-added activities in the future. This particularly fits to the case of developing countries and we examine whether and to what extent this is the case of mining technologies in Chapter 2 and especially Chapter 3 of this thesis.

Deep relationships of some sorts between technical change and economic development are now generally acknowledged in both economic history and economic theory (Cimoli and Dosi, 1995). Specifically, the "sectoral heterogeneity" in technological opportunities provides the fundamental connection between structural change, technical progress and aggregate economic growth, since it implies that the overall pattern of economic growth will be essentially shaped by the shifts in the sectoral composition of output (Nuvolari and Russo, 2021). One of the main goals of this thesis is to examine technological change in the mining industry and, more precisely, how mining technologies evolve on the international technological frontier over time. We use the notion of technological trajectories and technological paradigms (Dosi, 1982) as a tool to identify frontier technologies. Nuvolari and Russo (2021) state that the key point stressed by "neo-Schumpeterian" scholars is the emphasis on the critical role of discontinuities in the broad contours of technical change. These discontinuities are related to the successive deployment of a sequence of "technological systems" or "techno-economic paradigms". The notion of technological paradigm refer to constellations of major innovations characterized by strong technological and economic linkages, aimed at solving specific issues in an industry (Dosi, 1982). This thesis identifies the presence of technological paradigm(s) in the mining industry, detecting eventual paradigmatic shifts of technological change during time, and attempting to study the reasons behind these paradigmatic changes of technical advances in mining. The concept of technological trajectories is associated to the progressive realization of the innovative opportunities associated with each technological paradigm, which can in principle be measured in terms of the changes in the fundamental techno-economic characteristics of artifacts and the production process (Nelson, 2008b). Cimoli and Dosi (1995) argue that the core ideas involved in this notion of trajectories are the following. First, each particular body of knowledge (i.e. each technological paradigm) shapes and constraints the rates and direction of technological change irrespectively of market inducements. Second, as a consequence, one should be able to observe regularities and invariances in the pattern of technical change which hold under different market conditions and whose disruption is correlated with radical changes in knowledge-bases (in paradigms). Third, technical change is partly driven by repeated attempts to cope with technological imbalances which itself creates. This is akin to the notion of technological path dependence (our second key issue) and technological bottlenecks (Rosenberg, 1976). Relatedly, this thesis investigates whether technological trajectories are technology bounded, i.e. path dependent in the mining sector. The quantitative methodology developed in this thesis to identify technological trajectories in the mining sector is main path analysis (Hummon and Doreian, 1989; Liu and Lu, 2012), using patent citation networks. Main path analysis is a network method capable of tracing the most significant paths in a citation network and is commonly used to trace the development trajectory of a technology field (in our case mining). Chapter 3 of this thesis contains a thorough illustration of the precise methodology of main path analysis adopted using the software "Pajek" for social network analysis (De Nooy, Mrvar and Batagelj, 2018).

1.2.3 The potential innovativeness of the METS companies and their linkages with mining firms

A relevant problem for the mining industry, among others, is removing geographical barriers (considering that mining activities are sometimes carried out at high altitudes and/or in remote locations) and facilitating backward and forward linkages (Figueiredo and Piana, 2016; Hirschmann, 1977) between mining companies and third parties (e.g. suppliers) even through transport technologies related to mining processes (Bartos, 2007; Daly, Valacchi and Raffo, 2019; Molina, Olivari and Pietrobelli, 2016).

Over the past decades, the mining industry has had to face a challenging scenario for its operation. Improving productivity to overcome natural factors such as decreasing ore grades, deeper deposits and harder rock mass, combined with an increasing environmental and social awareness, has boost the industry to constantly work to enhance their processes along the whole value chain, where suppliers to mining companies are often present. In this, innovation plays a crucial role by providing suitable solutions to surpass these difficulties, ensuring the continuity and sustainability of the mining activity (Sanchez and Hartlieb, 2020).

A series of changes in corporate strategies, the emergence of digital transformations and other new technologies, among other factors, have led to a de-verticalization of the mining industry. "The world looks at mining as one industry, but it is a collection of industries with different supply and demand dynamics" (Deloitte, 2017; p. 1). Hence, the dynamics for innovation are better understood by looking at the different industries which comprise the mining industry, and that are carried out along a value chain (Calzada Olvera, 2021; Pietrobelli, Marin and Olivari, 2018). It is worth briefly describing the mining value chain from upstream to downstream stages. The exploration stage includes activities such as ore body discovery, mineral determination, resource estimation and feasibility studies. The mining operation stage includes activities such as mine planning, design and development, mine construction, extraction of ore bodies and mineral processing. Once the mineral has been processed, then refining can occur. Each stage of the process is supported by services, e.g. transport, waste treatment and energy generation (Daly, Valacchi and Raffo, 2019).

In this thesis, we consider the mining industry as a collection of firms that innovate in mining technologies (not only those that produce mineral commodities) and may belong to other industries, different from mining. Considering that innovation in the mining sector is supplier-dominated according to the Pavitt taxonomy (Pavitt, 1984), in addition to mining companies, we include suppliers to mining firms, i.e. METS companies in our analysis following extant literature (see e.g. Daly, Valacchi and Raffo, 2019; Fernandez, 2021; Humphreys, 2019; Iizuka, Pietrobelli and Vargas, 2019). We refer to Appendix B in Chapter 4 of this thesis for a list of NACE Rev. 2 classification codes regarding the economic sector to which the METS firms included in our analysis belong. For the sake of precision, in this context, in the definition of "mining industry", in our empirical analyses we include metallic and non-metallic minerals[10] and coal, but not other fossil fuels different from coal, e.g. oil and natural gas considering that the processes and technologies utilized are relatively different one from another especially after the initial (i.e. extraction) value chain stage.

It is important to notice that innovation helps solving key issues in the mining industry. For instance, as already mentioned, the mining industry is not excluded from environmental challenges, e.g. the effects of global warming and increasing greenhouse gases emissions (Iizuka, Pietrobelli and Vargas, 2019; Katz

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[10] For example, metallic minerals include copper, gold, silver, zinc, cobalt, tin, nickel, lead, aluminium. Non-metallic minerals may include, among others, lithium, sand, gravel, marble.

and Pietrobelli, 2018). Albanese and McGagh (2011) state that mining companies have no choice in taking sustained actions to reduce the environmental impact of their operations; otherwise, if they do not reduce the size of their footprint, the governments who are in a position to give them a mineral concession to operate will no longer do so. Innovation is also essential to support the exploration phase, which is at the beginning of the mining value chain (Daly, Valacchi and Raffo, 2019). The exploration stage is costly, risky and uncertain (Calzada Olvera and Iizuka, 2020; Kreuzer and Etheridge, 2010). In effect, history has repeatedly shown that the probability of converting exploration targets into economic deposits is low. In the future, therefore, the key challenge for exploration geology is to increase this probability of success by the identification of a wider range of deposit types, including lower-grade ores, deposits with different mineralization styles, and ores with greater variability, possibly in areas already explored because it would be more convenient (Albanese and McGagh, 2011).

Calzada Olvera and Iizuka (2020) state that the mining industry 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. Involvement in GVCs (Global Value Chains) can offer opportunities for the suppliers of mining firms to innovate (Iizuka, Pietrobelli and Vargas, 2019; Pietrobelli, Marin and Olivari, 2018). This refers to possible opportunities for technological (and mining products) upgrading along the mining GVC, as a means to reduce the volatility of markets (UNCTAD, 2013). This thesis examines these upgrading opportunities along the mining value chain for Latin America in Chapter 2. In some developing resource-rich countries, backward linkages do not exist (or are very weak) because machinery purchase and service is likely to be imported from abroad. The reason why is that the host country does not have an advanced secondary sector (Andersen et al., 2015) and mining companies prefer to rely on foreign suppliers instead of local suppliers, e.g. in Latin America (Pietrobelli, Marin and Olivari, 2018) (see chapter 2 on this). This goes against the chance to promote technological upgrading into higher value added activities along the mining GVC.

Innovation in the extractive sector is the result of a complex business ecosystem conformed by machinery equipment manufacturers, service providers, mining and junior firms, academia and other organizations. In the case of developing resource-rich countries (e.g. Latin America), such ecosystem is still underdeveloped despite the importance of the industry. Suppliers in these developing countries are quite heterogeneous in terms of their technological and organizational capacities and most of the interactions between mining firms and suppliers can be described as transactional rather than collaborative (Calzada Olvera, 2021).

In the mining sector, a new context is emerging, which is opening new opportunities for innovation and fruitful linkages between lead firms and suppliers to mining companies, i.e. METS (Mining Equipment Technology Services) firms which did not exist before (Bravo Ortega and Munoz, 2015; Perez, 2010; Marin et al., 2015). These new opportunities are associated with a larger and more diversified demand for natural resources, new knowledge and technology advances applicable to these sectors, outsourcing along GVCs, together with the search for local technological solutions and an increasing pressure to innovate to reduce environmental impact (Iizuka and Katz, 2015). Nevertheless, value chains with the typical characteristics of mining GVCs may have governance structures that might to some degree generate a market failure for innovation (Molina, Olivari and Pietrobelli, 2016). This is particularly true in emerging countries where the local and national innovation system could not provide the underlying knowledge base for the suppliers to "upgrade" into the possible technological opportunities (Iizuka, Pietrobelli and Vargas, 2019). Relatedly, this thesis investigates whether diversification within mining innovation activities, carried out at different stages along the mining GVC, translates into technological upgrading within GVCs, which often means non-mining production (i.e. METS companies).

In the current global context and under the new structure of the extractive sector, new opportunities are emerging for the development of local suppliers associated to mining activities. It is worth stressing that the expansion of the natural resource sector may also enhance the diversification of productive activities through the development of domestic and knowledge intensive industries, which are suppliers and users to the natural resource intensive industries. This is equivalent to promoting the quantity and quality of backward and forward linkages (Hirschmann, 1977; Stubrin, 2018) around natural resource production including both manufacturing and service firms, as happened in Norway (Andersen et al., 2015; Fagerberg, Mowery and Verspagen, 2009). Therefore, it is also important that the knowledge developed in relation to natural resources intensive industries "migrates" to other areas of application that are not linked directly to resource production (Lorentzen, 2006). These "lateral" knowledge migration linkages are thus key vehicles of technological diversification induced by activities related to natural resources. It is only rather recently that this has received attention in relation to natural resource intensive economies, especially in developing countries (Andersen et al., 2015). Furthermore, diversification should not only entail productive activities, but also innovation activities (Andersen et al., 2015; Hidalgo and Hausmann, 2009) (see Chapter 4 of this thesis on the impact of technological diversification within the mining sector on companies' profitability). A country's diversity of capabilities tend to influence its ability to develop new capabilities, and the speed with which this process unfolds. Thus, an economy with low diversity (as is the case with many developing countries) will, ceteris paribus, have larger challenges in diversifying further and initiating longer term growth (Hidalgo et al., 2007). It is well-known that innovation most often arises from new combinations of existing items of knowledge (Schumpeter, 1934) and that in turn generates novelty and increased diversity. Hence, diversity strengthens innovation potential. When seen from a linkages perspective, the more diversity an economy contains, the larger is the potential for the emergence of new linkages and for innovation. METS firms play a key role on this (Fernandez, 2021). Fagerberg (1992) states that export diversification begins with learning and capability building in domestic resource-abundant countries. In this regard, having access to a home market than can serve as a "learning arena" via local-user producer interaction can be an important factor for successful diversification (Bell, 2006).

1.2.4 Mining innovation, technological diversification and firms' profitability

It is also worth stressing the key role that cost reduction plays in mining innovation, which is rooted in the undifferentiated, unvarying nature of mining commodities. Cost reduction is an important driver of mining profitability (Humphreys, 2019). Regardless of the complexity of technologies involved in the process of exploration, exploitation and post-exploitation, the final product will be the same: "copper is copper, gold bullion is gold bullion" (Bartos, 2007). Since there is no room for product differentiation, several mining firms compete on the basis of price as opposed to product characteristics (Porter, 1980). In turn, this will imply that the industry will innovate through the adoption of technologies throughout the various stages of the supply chain and, thus, it is characterized by process innovations, instead of product innovations (Calzada Olvera, 2021; Calzada Olvera and Iizuka, 2020).

Crowson (2001) argues that the large number of producers with differing costs, regulatory systems, the relatively low barriers to entry and the pervasive anti-trust laws of the industrial countries rule out effective collusive action to raise prices. In any case, the ever-present threat of substitution by other metals, materials and technologies limits the scope for supporting prices much above the marginal costs of production.

Considering the crucial role that innovation plays in encouraging a natural resource-based industrialisation strategy for (developing) resource-abundant countries (Andersen et. Al, 2015; Perez, 2015) and the prevalent cost-cutting nature of mining innovations (Humphreys, 2019; Iizuka, Pietrobelli and Vargas, 2019), in this thesis we examine whether and to what extent it is convenient, and thus profitable, for companies to carry out innovation activities in the mining industry (this relates to our fourth key open issue mentioned in Section 1 of this introduction and addressed in Chapter 4 of this thesis).

With reference to a broader context, Bogliacino and Pianta (2012) state that the effect of innovation on profits is not simple to disentangle. At the industry level, the link clearly emerges, as sectors with higher innovation – through both direct effects and spillovers – end up showing higher profit dynamics (Pianta and Tancioni, 2008). Conversely, at the firm level, a high heterogeneity is found; a few firms have innovative success, market expansion and high profits; others may innovate without obtaining significant profits owing to firm-specific factors (business strategies, cost structures and so on) or to market conditions (e.g. competition); others may yet show high profits that result more from market power than from innovation. A part of the existing literature (see e.g. Cerulli et al., 2021; Hanel and St-Pierre, 2002) finds that firms can experience in the short run a negative effect of patented innovations on profitability, considering that the denominators of the profitability indices capture additional costs associated to patenting activity (Grabowski et al., 2002). In fact, this negative impact of innovation on profitability may be based on the additional investments required to realize such innovation activity.

In the mining industry, a viable strategy to make profits is to invest solely in prospectively low-cost operations and keep costs under rigid control throughout the mining life cycle (Crowson, 2001). Humphreys (2019) and Tilton (2014) identify the drivers that shape changes in economic performance and profitability in mining. These drivers include resource depletion and ore quality, government regulations, worker quality, innovation and technological change, economies of scale, investment lags, strikes and other unplanned production stoppages, and other factors such as management, organisation and market structure. In modern times, the mining industry has focussed relentlessly on short-term profitability (Deloitte, 2017). Mining firms increase the linkage with suppliers (backward linkages) when mineral prices decline to carry out cost-reducing innovation (e.g. customization, the introduction of digital technologies) and to maximise profits (Calzada Olvera and Iizuka, 2020).

The quintessential goal of strategy research is to understand what accounts for differences in profitability across firms. One factor that might impact on the relationship between innovation and profits is the level of innovation's appropriability. The strength of strategies used to appropriate innovation rents such as patenting, secrecy, exploitation of first-mover advantages, and ownership of specialised complementary assets, is therefore a key determinant of profitability differences across firms (Ceccagnoli, 2009). In particular, appropriability refers to the degree to which a firm captures the value created when it introduces (patented) innovations (Hanel and St-Pierre, 2002; Winter, 2006). It is worth stressing that Cockburn and Griliches (1988) show that returns to innovation, as measured by the market valuation of a firm's intangible assets, is critically affected by appropriability conditions. Furthermore, Ceccagnoli (2009) finds that greater appropriability, achieved through patent protection, as well as the ownership of specialised complementary assets, has a large, positive and significant impact on a firm's economic performance. In the context of the mining industry, the knowledge upon which supplier-dominated innovations is based has a low level of appropriability (Calzada Olvera and Iizuka, 2020). This means that it is costly to profit from knowledge generated from its diffusion and broader application; thus, firms are less inclined to invest in innovation. This may represent one reason why (among others) we find in Chapter 4 of this thesis a negative and significant relationship between overall mining innovation on firms' profitability, after having set up a profitability model, i.e. a panel fixed effects econometric model (see details on the empirical strategy in Chapter 4 of this thesis).

Beyond levels of innovation, a related and relevant issue is whether and to what extent technological diversification regarding mining innovation activities carried out at different stages along the mining value chain may affect firms' profitability. We address this issue in Chapter 4 of this thesis building on extant literature on this topic. Technological diversification at the level of the firm regards the expansion of a firm's technology base into a wide range of technology fields or into a wide range of technology sub-fields within a technology field (e.g. mining) (Granstrand and Sjolander, 1990; Leten, Belderbos and Van Looy, 2007). In fact, considerable variance in technological diversification levels remains among firms within the same sector. This variance reflects the different bets made by management in the face of technological complexity and uncertainty (Nelson and Winter, 1977). One of the driving forces that has been advanced to explain the technological diversity of firms' technology portfolios is the increasing complexity of products and production processes over time, making it necessary for companies to invest in a variety of technology fields (Rycroft and Kash, 1999; Piscitello, 2004). Patents can be regarded as an important technological output to explain firms' innovative capabilities and can be used as a useful source to trace firms' technological diversification and concentration strategy (Hall, Jaffe and Tratjenberg, 2001; Kim, Lim and Park, 2009; Pugliese et al., 2019). Granstrand and Sjolander (1990) state that technological diversification might be a key strategic variable that has a stronger impact on profitability and growth than traditional strategic variables such as internationalization (degree of multinationality), product diversification and R&D intensity. However, the relationship between technological diversification and economic performance may be non-monotonic and perhaps U-shaped. Hence, a company may run the risk of becoming too multi-technological. After all, there is a limit to the ability to manage multi-technology operations (Granstrand and Sjolander, 1994; Patel and Pavitt, 1997). More precisely, a firm should determine whether it would invest intensively in its core technology field (or core technology sub-fields within a technology field) or broadly across non-related technology fields (technology sub-fields within a technology field[11]). Consequently, a firm's financial performance can be affected by its technological diversification as a form of R&D strategy (Kim, Lim and Park, 2009). In this context, there exist limits with respect to the net benefits of firms' technological diversification and too much diversification may negatively impact technological and economic performance (Leten, Belderbos and Van Looy, 2007). Firms can increase the benefits of diversification and limit the disadvantages by choosing the direction of diversification carefully and extending their activities into technology fields that share a common knowledge base with the firm's existing technology portfolio. This corresponds to the definition of coherent (related) technological diversification, which is different from random (unrelated)

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[11] In our case, we refer to the nine mining-related technological sub-fields within the technological field "mining", i.e. exploration, blasting, mining (mine operation), environmental, transport, automation, processing, metallurgy and refining technologies.

technological diversification[12] (Dosi, Mathew and Pugliese, 2021; Nesta and Saviotti, 2005; Pugliese et al., 2019). Thus, technology characteristics (e.g. technological relatedness) should be taken into account when taking strategic decisions on the composition and organization of technology portfolios. For instance, Gort (1962) empirically analysed the relationship between technological diversification and profitability using data collected between 1947 and 1957 of 111 large enterprises in the US, and confirmed that there was no significant relationship between diversification and profitability. In contrast, Rumelt (1974) showed that companies that diversified their core (central) competence had better economic performance than other companies. Moreover, Christensen and Montgomery (1981) indicated that companies that experienced diversification in related fields had a higher profitability than companies that experienced diversification in unrelated fields. Pugliese et al. (2019) find that the coherent technological diversification of firms is quantitatively related with their economic performance and captures relevant information about their productive structure. Furthermore, Pugliese et al. (2019) find that though (total) technological diversification is statistically significant if used alone, it loses explanatory power when used in the same model as coherent technological diversification. This is particularly interesting because it suggests that the number of connected technologies within the technological knowledge portfolio of a company, as quantified by their measure of coherence, is more relevant than the raw number of technological fields in which the company innovates.

1.3 Outline of the thesis

Given all the above discussion, this thesis is divided into three substantive chapters.

Chapter 2 builds on the rationale behind this general introduction, i.e. that fostering innovation in the mining industry is a key aspect to rely upon, in order to encourage economic development of resource-endowed countries (e.g. Latin America) and to avoid resource curse. Specifically, the chapter examines the trade and innovation specialization patterns in the Latin American mining sector. Large parts of Latin America are often considered to be following a natural resource-based development strategy, taking advantage of the economic rents conferred by privileged access to abundant natural resource endowments (Alcorta and Peres, 1998; Cimoli et al., 2006). Several Latin American countries, in particular, exhibit a substantial specialisation in the extraction and export of mining products. In recent times, such an approach can be considered to represent an important development opportunity for developing resource-rich countries, an opportunity arising from favourable global conditions associated with the increased demand for minerals alongside dwindling supplies from easy-extraction mines (Marin, Navas-Aleman and Perez, 2015).

Without efforts to upgrade and diversify, such a strategy based on a heavy reliance on natural resources is associated with a strong risk that development efforts will be unsuccessful. This connects to our first key research question illustrated in Sections 1 and 2.1 of this introductory chapter. In fact, production specialisation without innovation specialisation can lead to a lack of long-run development (Cimoli and Porcile, 2011; Dosi and Tranchero, 2021). When economic rents are purely based on the relative abundance of resources without fostering innovation, the capacities to respond to shocks and changes is reduced, since the country basically lacks the technological capabilities necessary to readapt the production system to changing contexts (Cimoli et al., 2006). Furthermore, in Latin America, firms

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[12] Total technological diversification (or technological diversification) is the sum between random and coherent technological diversification. We will use the terms total technological diversification and technological diversification interchangeably.

operating in the natural resources sector have become more closely integrated to global chains of value in which the stimulus to speed up indigenous learning was abandoned in favour of a focus on homogenization of inputs and goods within a hierarchical system of production (ECLAC, 2008). This occurred in parallel with the progressive commoditization of the production of goods and services in the Latin American region.

Based upon these arguments, Chapter 2 considers four main issues. Firstly, the it presents information on the production and specialisation patterns of Latin America in mining products, highlighting that Latin America is indeed specialised in the extraction and export of mineral commodities, with the mining sector also being a major target for inward FDI into this set of countries. Secondly, the paper examines whether a similar specialisation pattern is also observed when using patent data to examine whether Latin America is specialised in the production of technology (i.e. innovation) in the mining sector (our first key research question stated in Section 1 and Section 2.1 of this introductory chapter). The results suggest that Latin America is not specialised in the production of mining technologies, but is instead a user of technologies developed elsewhere. Thirdly, and relatedly, the chapter addresses whether Latin America is specialised in the production and export of mining equipment, addressing the question of whether Latin America has been able to develop production capabilities in this upstream activity, where the potential to capture a higher value-added share from the mining value chain is potentially larger (Blundi et al., 2019; Xu and Chiang, 2005). The results suggest that Latin America has not been able to develop specialisation in mining equipment, instead relying on imports to serve its own needs regarding mining equipment. This confirms that the creation of backward linkages between mining companies and their suppliers at the local level (Hirschmann, 1977) is hindered by the fact that machinery and advanced services are largely imported from abroad, let alone the possibility that the host region may not even have an advanced secondary sector. This answers our third key issue discussed in Section 1 and in Section 2.3 of this general introduction. Fourthly, we investigate the quality of Latin American innovation in the mining industry in two different but complementary ways: by examining whether Latin America is specialised in the production of cutting-edge mining technologies and by investigating the quality of the mining patents invented by Latin American applicants using patent value indicators (OECD, 2009).

(Appendix E in Chapter 2 builds on the rationale behind this general introduction and on some related findings in Chapter 2, by providing a short case study on a developing resource-abundant country, i.e. Peru. In this context, we show the presence of some structural weaknesses (e.g. the lack of diversification of productive activities and the lack of innovation) that are favoured by, and associated with, the specialisation (dependence) on natural resources production. This relates to our first key research question described in Sections 1 and 2.1 of this general introduction (i.e. Chapter 1).

Chapter 3 further addresses the key theme of innovation and technological change in the mining sector at the global level, specifically focusing on frontier technologies. This allows to identify the more persistent innovation patterns, and that find many implementations in the context of the mining sector.

In particular, we use patent citation networks (network analysis) to study the dynamics of technological change in the mining sector, i.e. developments on the mining technological frontier between 1970 and 2015. We examine the patterns of patenting activities in mining – particularly in the case of cutting edge innovations, i.e. those that have had the highest impact on subsequent innovations – and examine how they span across technological fields/regions/players. This regards the answers to our third key research question described in Section 1 and Section 2.2 of this introductory chapter.

In Chapter 3, the use of connectivity indicators and a search algorithm allow us to identify a set of patents connected by direct citations that constitute the "main path", i.e. the main flow of knowledge within the network of patents citing each other over time (Mina et al., 2007; Chen, Shih and Liu, 2020). These citation links capture subsequent problem-solving information and the underlying heuristics embedded in a patent are illustrative of an ordered path of global, cumulative and irreversible technical changes (Martinelli, 2012). In this sense, the main flow of knowledge accomplishes the definition of technological trajectory put forward by Dosi (1982).

The analysis of the connectivity of patent citation networks has important implications for assessing the relevance of innovations in large technical systems. In fact, it allows identifying technologically significant patents, the ones belonging to the "main paths" of the citation networks. Another merit of this approach is that, by reconstructing technological trajectories as sequences of patents, it opens the opportunity for a fruitful reconciliation between quantitative and qualitative insights in the study of technical change in specific domains, mining technologies in our case. Indeed, the approach allows to pin down a restricted number of patents, whose content can then be examined in detail. By reading the content of these patents, it is possible to reconstruct the heuristics governing inventive activities and go beyond the assessment of innovation patterns based only on patent counts (Fontana, Nuvolari and Verspagen, 2009).

In addition, Kalthaus (2019) points out that analyzing technological change at the sub-trajectory level helps us to understand its mechanisms and drivers in greater details, since patterns characterizing specific knowledge fields might be indistinguishable at the more aggregate trajectory level, but they might contribute to determine substantial technological improvements. In other words, significant innovation may be occurring at the sub-trajectory level that is not captured by the overall trajectory (Kalthaus, 2019). Thus, our analysis is further detailed at the sub-trajectory level by considering nine mining-related technological fields: exploration, blasting, mining (mine operation), processing, metallurgy, refining, environmental, automation and transport technologies. These nine sub-networks represent the nine technological sub-trajectories within mining.

Consistent with previous literature focused on other technological domains, we find that innovation patterns are "technology bounded" in the mining sector, i.e. they are largely shaped by patenting activities carried out in a very limited range of largely persisting mining technological fields (with the only relevant exception of a shift from exploration to environmental technologies at the beginning of the 2000s). These cumulative patterns of innovation signal the emergence of a new technological paradigm characterising inventive activities in mining (Dosi, 1982; Martinelli, 2012). A similar pattern of technology boundedness (technological path dependence) holds for the sub-trajectories, with the partial exceptions of the refining and blasting sub-trajectories that are less technology bounded than the others.

In addition, we examine two aspects of technical change that have been largely disregarded in extant research: the geographical patterns of inventive activities and the role of key applicants in such patterns.

We show that the core mining patents and leading inventors involved originate almost exclusively from the US, so that trajectories appear to be heavily geographically bounded across countries. This finding reveals that developing resource-abundant countries lag behind the technological frontier in mining. For instance, Latin America (a developing resource-abundant region) is not present at the trajectory and at the sub-trajectories level, with the only (partial) exception of the sub-trajectory "Mine operation", where 20% of the inventors of its core mining patents are from Argentina. This might to do with the very high costs of these leading mining innovations that prevent developing countries from the opportunity of creating this "core" mining knowledge. Hence, the developed world (almost exclusively the US) produces the mining technologies on the international technological frontier, revealing the presence of a hierarchy that consolidates in markets over time: first comers in innovation continue to lead innovation processes over time, completely excluding the developing world from these potentially fruitful opportunities of knowledge creation, which might foster economic development. We also find that all the mining patents in the "top main path" (i.e. the largest flow of knowledge stemming from the most cited and citing patents, at the same time) of the trajectory and of the sub-trajectories are filed only (in the case of the trajectory and of most of the sub-trajectories) or mainly (the case of a few sub-trajectories) in the US. This reveals that knowledge diffusion across countries is virtually absent. Given the lack of developing and emerging economies in the production of frontier technology and given the limited diffusion of this knowledge to these countries, the extent of upgrading and technological development in mining in developing and emerging countries may be very limited, placing a substantial constraint to their development opportunities.

Moreover, we carry out an analysis of the portfolio of mining patents owned by the 10 companies that are in the largest flow of knowledge on the technological trajectory in order to examine to what extent these mining technologies have diffused to developing countries that have not generally been involved in innovating in the sector to any extent. We find that developing resource-rich countries (e.g. Africa and Latin America) are neither producers nor users of the ten companies' mining technologies, with the partial exception of Latin America that uses some of their technologies.

As a last step, we discover that only a few applicant firms are responsible for most inventive activities (oligopolistic structure), hence characterizing trajectories as "applicant bounded" as well, with the partial exception of the Mine operation, processing and transport sub-trajectories that are less applicant bounded. Relatedly, we find that certain firms help develop the trajectory and the way in which the trajectory develops may exclude some firms from entering and competing, leading to a narrow set of firms driving the trajectory. Then, one of the few ways in which new firms can enter (easing technological boundedness) is through the development of a new paradigm, e.g. a movement from exploration to green technologies at the trajectory level. The emergence of the new technological paradigm on environmental technologies related to mining activities at the early 2000s is motivated by institutional factors (Dosi, 1982), i.e. stricter environmental policies at the national level that compel firms to carry out green innovation activities, even considering a greater societal awareness of the pollutant potential of the mining industry (Andersen and Noailly, 2019). Relatedly, except for governmental policies, it is not convenient to invest in green mining innovations for companies. This is empirically confirmed by our results in Chapter 4 of this thesis, where we find, through an econometric analysis, that environmental mining technologies have a negative and significant impact on firms' profitability.

Considering that innovation is crucial to achieve natural-resource based development (especially for developing countries), **Chapter 4** addresses the issue of whether carrying out mining innovation activities is profitable (and thus convenient) for the firms innovating in mining technologies at the global level. To explore this aspect, we build a panel fixed effects econometric model of profitability as a function of innovation patterns in mining. In this context, we use Return on Assets (ROA) as measure of profitability and dependent variable[13]. Chapter 4 of this thesis answers our fourth research question that has been illustrated in Sections 1 and 2.4 of this introductory chapter.

We combine WIPO data on the patenting activities of over 245,000 companies with specific reference to nine mining technologies in 1970-2015 with Orbis data on these firms' profitability in 2010-18. Our results show that mining companies' innovation activities have on average a negative effect on their profitability in 2010-2018, reflecting the high costs of innovation in this field and a conservative attitude of firms in most segments of the mining value chain. This seems to be consistent with the idea that innovation, apart from the introduction of cost-cutting technologies (which occurs in a relatively restricted array of cases anyways) is not in the top priorities for mining companies and it is not among the main drivers of profitability (Batterham, 2013; Ernst & Young, 2010). In addition, the negative impact of overall mining innovation on profits may also relate to the low level of appropriability of innovation in the mining industry (Calzada Olvera and Iizuka, 2020). It is worth noting that the dynamics for innovation are better understood by looking at the different industries which comprise the mining industry and that are carried out along a value chain (Calzada Olvera, 2021; Stubrin, 2018). In fact, in recent decades, mining companies have increasingly organised their activities along GVCs (Global Value Chains) (Iizuka, Pietrobelli and Vargas, 2019; Pietrobelli, Marin and Olivari, 2018) and this may offer strengthening linkages among firms and other actors. This chapter digs deeper into the impact of mining innovation on profitability taking into account a GVC perspective. We disentangle the heterogeneity of innovations within the mining sector, assuming that different mining technologies may have a different impact on the companies' profitability. More precisely, we divide the total portfolio of mining patents of the firms innovating in mining technologies into 9 "sub-portfolios", i.e. mining technological fields in the WIPO Mining Database. These nine "sub-portfolios" (blasting, exploration, mine operation, processing, metallurgy, refining, automation, environmental and transport technologies) of mining patents represent different stages along the mining GVC, with a different potential impact on the corporate's profits.

Innovation in blasting and metallurgy technologies makes a relevant exception to the mining technologies as a whole, as patenting in this field appears to have a strong and significantly positive effect on firms' profits. This might have to do with the nature of such technologies which are both cost-cutting and applicable to a variety of different contexts within and across the boundaries of the mining industry (general-purpose technologies, see e.g. Bresnahan and Trajtenberg, 1995; Conti, Gambardella and Novelli, 2019), hence yielding higher profits. Instead, environmental technologies have a negative impact on profitability – at least in a relatively short run – because they are more sector-specific and they compel firms to bear compliance costs due to stricter environmental regulations at the national level.

Beyond levels of innovation, a related stream of literature investigates the relationship between corporate technological diversification and economic performance, e.g. profitability (Palepu, 1985). This is an issue of considerable interest to both academics and managers. Technology diversification is defined as the corporation's expansion of its technological competence into a broader range of technological areas (Granstrand and Oskarsson, 1994).

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[13] It is worth noticing that our main findings of Chapter 4 are confirmed by two robustness analyses, i.e. a cross-section analysis of year 2012 and a panel fixed effects model using a different profitability measure which is Return on Equity (ROE).

The arguments in the industrial organization literature linking diversification to profitability (one measure of economic performance) revolve around the notion of market power (Markham, 1973). Because of its ability to acquire and exercise market power, a technologically diversified firm is alleged to be able to subvert competitive market forces through mechanisms such as cross-subsidization, predatory pricing, reciprocity in selling and buying and barriers to entry. Another mechanism that is expected to allow diversified firms to sustain supernormal profits is the "information loss" that arises from the ability of a diversified firm to conceal the profitability of its individual business segment (Palepu, 1985). These arguments lead to the concept that the more diversity a firm has in its technological competencies, the better are its chances of extracting profits (Piscitello, 2004). However, it does not always happen that technological diversification has a positive impact on firms' economic performance (Dosi, Mathew and Pugliese, 2021). Possible explanations for this might relate to the importance of sector-specific knowledge or the greater fixed costs of innovating across many and unrelated fields. In fact, the existing evidence on the relationship between technological diversification and firm economic performance has shown that, instead of "total[14]" technological diversification, coherent technological diversification usually has a positive impact on firm performance (e.g. profits) because it is less costly (see e.g. Piscitello, 2004; Pugliese et al., 2019). When the different technology fields (or technology sub-fields) share a similar underlying knowledge base, a firm's technology portfolio is considered as technologically coherent (Kim, Lim and Park, 2009; Leten, Belderbos and Van Looy, 2007; Nesta and Saviotti, 2005).

We find that being technologically diversified in terms of innovation activities across different stages of the mining value chain negatively affects the companies' profits. One reason for the negative relationship could be that more (random) technological diversification involves less coherence in firm's technological competencies.

This might reveal that it is less costly (and more profitable) to develop mining innovations that are related to the firms' core technological competencies. In fact, when a firm operates in a set of "related" technologies, it is possible for it to exploit its "core factors" leading to economies of scale and scope, efficiency in resource allocation and opportunity to exploit particular technical and managerial skills (Palepu, 1985; Pugliese et al., 2019; Rumelt, 1982). This brings opportunities to increase profits.

Overall, the analysis conducted in this thesis highlights the potential tensions between country – and industry - level development opportunities that are associated with innovation and with broader specialisation patterns, going beyond mining industry alone; and firm level propensity to adopt conservative, low innovation and low diversification strategies, given the nature of technologies at stake and of appropriability conditions. From this perspective relatively underdeveloped, resource abundant economies may be bound not to escape the poverty trap, unless innovation oriented public policies are undertaken at the national and supra-national levels to overcome the low private incentive to innovate.

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[14] It is worth remembering that total technological diversification is the sum of random technological diversification (across many and unrelated technology fields) and coherent technological diversification (across few and related technology fields). In this thesis, for the sake of brevity, we refer to total technological diversification using the term technological diversification.

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Chapter 2

Innovation and Trade Patterns in the Latin American Mining Sector[♦]

Abstract

This paper examines the trade and innovation specialization patterns in the Latin American mining sector, in terms of exports of mining products, of its exports of mining equipment, and of its production of mining technologies (i.e. innovation). Results suggest that Latin American countries are specialised in the extraction and export of mining products (i.e. minerals), and de-specialised in the production of mining equipment and of mining technology, while they heavily rely on imports of equipment and technology. We also find that the mining innovation taking place in Latin America is of relatively low quality. Considering that innovation in the mining sector is supplier-dominated, the weak technological specialisation of Latin American countries in the mining sector reflects mainly the low innovation capacity of local suppliers to mining companies, in comparison to the global average.

Keywords: Mining innovation; Mining production; Specialization patterns; Patent quality indicators; Local METS (suppliers); Patents; Trade data; Inward FDI; Latin America

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2.1 Introduction

Large parts of Latin America are often considered to be following a natural resource based development strategy, taking advantage of the economic rents conferred by privileged access to abundant natural resource endowments (Cimoli et al., 2006). A number of Latin American countries exhibit a strong specialisation in the extraction and export of mining products, although there is heterogeneity across countries within Latin America on this. Such an approach can be considered to represent an important development opportunity for developing resource-abundant countries, an opportunity arising from favourable global conditions associated with the increased demand for minerals alongside dwindling supplies from easy-extraction mines (Marin, Navas-Aleman and Perez, 2015).

However, a national resource based development strategy is quite risky if not accompanied by substantial efforts to upgrade and diversify both within and beyond the natural resource sector (Pietrobelli and Rabellotti, 2011). Cimoli et al. (2006), for example, argue that the abundance of resources can sustain growth without significant efforts for learning in the short term, but that in the long-run economic rents derived from these resources tend to be eroded. Moreover, in the context of dwindling supplies and the necessity to extract natural resources from more difficult locations, innovation is increasingly necessary as a means of achieving profitable mineral extraction from less favourable locations or from lower quality mines. Such innovation efforts would encompass processes related to exploration, extraction and transportation technologies (Molina, Olivari and Pietrobelli, 2016). In other cases, especially when natural resources are abundant, but labour is scarce, significant technological efforts may be required to boost labour productivity (e.g. the case of Latin America). To summarise, production specialisation without innovation specialisation can lead to a lack of long-run development[15] (Cimoli and Porcile, 2011; Dosi and Tranchero, 2021). When economic rents are purely based on the relative abundance of resources without fostering innovation, the capacities to induce or respond to shocks and changes is reduced, since the country basically lacks the technological capabilities necessary to readapt the production system to changing contexts (Cimoli et al., 2006). Furthermore, in Latin America, firms operating in the natural resources sector have become more closely integrated in to global value chains in which the stimulus to speed up indigenous learning was abandoned in favour of a focus on homogenization of inputs and goods within a hierarchical system of production (ECLAC, 2008). This occurred in parallel with the progressive commoditization of the production of goods and services in the Latin American region. These processes jointly resulted in a disarticulation of local production chains along with the marginalization of small and medium domestic firms. Rationalization based on the more intense use of imported inputs and equipment produced blanks in the production matrix and had negative effects on the levels of employment and heterogeneity (Cimoli and Porcile, 2011).

Moving beyond innovation to consider a broader value chain perspective, it is also the case that the extraction and export of mining products is not necessarily the optimum positioning for countries to target in the value chain. While the processing and refining of mining products has often been considered a possible channel for upgrading within mining value chains (Kaplan, 2012; Pietrobelli, Marin and Olivari, 2018), a further relevant dimension relates to the production and export of upstream mining related products, such as mining equipment. Besides technological learning processes, knowledge-intensive

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[15] Learning and innovation reshape international competitiveness and allow countries to exploit the opportunities of international trade and growth (Alcorta and Peres, 1998). Furthermore, technological efforts are mediated by the transformation of the production structure. A structural change that promotes sectors that create and diffuse technology allows to capture the opportunities of international demand dynamism (Cimoli et al., 2006).

suppliers have been key for turning natural resource industries into knowledge-based industries with high innovation capabilities. Knowledge-intensive suppliers, from equipment to engineering services, have also been fundamental for the competitiveness of the industry itself, and the emergence of knowledge intensive clusters (Urzua, 2013). Bartos (2007) points out that much of the mining industry's present productivity and innovation have originated from outside the industry, specifically through equipment manufacturers and suppliers to the mining industry, with Mining Equipment Technology Services (METS) companies (i.e. suppliers) being key innovators for the mining industry (Bartos, 2007; Calzada Olvera, 2021; Daly, Valacchi and Raffo, 2019; Francis, 2015; Iizuka, Pietrobelli and Vargas, 2019; Scott-Kemmis, 2013; Urzua, 2003).

METS companies include equipment manufacturers, core engineering design & project management (EPCM), general and consulting services and specialized technology among others (Scott-Kemmis, 2013), which highlights the importance of linkages between the mining sector and other sectors in upgrading through mining activity. Marin and Stubrin (2015) point out that the extent of the linkages between the local economies and mining companies strongly depends on the technological capabilities of the local firms and the general economic and political context. Some production linkages can arise spontaneously, but if countries fail to actively encourage structural change it is likely that their specialization pattern will not automatically create the incentives to shift towards more sophisticated technological production stages and activities (Alcorta and Peres, 1998).

Moreover, the quality of mining innovation carried out at the local level in Latin America is another relevant factor to be examined in order to promote technological development. We study innovation quality in two different but complementary manners, i.e. selecting a set of cutting-edge (key) mining technologies and examining whether Latin America is specialised in producing them, and through patent quality. Concerning patent quality, as the number of patent applications has surged worldwide, economists and management scholars have become more and more dissatisfied with using simple patent application or grant numbers as an indication of innovation output (Gambardella, Harhoff and Verspagen, 2008). We measure the quality of local mining innovation using patent value indicators (Squicciarini, Dernis and Criscuolo, 2013). We use the term quality to emphasize both the technological and economic dimensions of an innovation (Lanjouw and Schankerman, 2004). For economists a good patent is generally one that fulfils the key objectives of the patent system, i.e. to reward and incentivise innovation while enabling diffusion and further technological developments. We use two main patent value indicators: the number of forward citations, i.e. references to previous patents (Jaffe and De Rassenfosse, 2017; Trajtenberg, 1990) and patent family size, i.e. the number of countries in which a patent is taken out (Putnam, 1996).

Based upon these arguments, this paper considers four main issues. Firstly, the paper presents information on the production and specialisation patterns of Latin America in mining products, highlighting that Latin America is indeed specialised in the extraction and export of mineral commodities, with the mining sector also being a major target for inward FDI into this set of countries. Secondly, the paper examines whether a similar specialisation pattern is also observed when using patent data to examine whether and to what extent Latin America is specialised in the production of technology (i.e. innovation) in the mining sector. The results suggest that Latin America is not specialised in the production of mining technologies, but is instead a user of technologies developed elsewhere. Thirdly, and relatedly, the paper addresses whether Latin America is specialised in the production and export of mining equipment, addressing the question of whether Latin America has been able to develop production capabilities in this upstream activity, where the potential to capture a higher value-added share from the mining value chain is potentially larger (Blundi et al., 2019; Xu and Chiang, 2005). The results suggest that Latin America has not been able to develop specialisation in mining equipment, instead relying on imports to serve its own needs regarding mining equipment. This confirms that the creation of backward linkages between mining companies and their suppliers at the local level (Hirschmann, 1977) is hindered, with machinery purchased from abroad, possibly reflecting that considered that the host region may not have an advanced secondary sector[16]. Fourthly, we investigate the quality of Latin American innovation in the mining industry.

The remainder of the paper is organized as follows: Section 2 describes the data used; Section 3 shows the results; based upon the results from the four main questions addressed, Section 4 summarises and proposes some explanations and implications of the observed results; Section 5 concludes.

2.2 Data

The paper relies on three main sources of data for the analysis. The first of these is the UN Comtrade database, which reports detailed product-level information on imports and exports of countries over time. For the analysis in this chapter, I rely on two main aggregates of this product-level data.

The first aggregate captures the export of mineral products, and includes metallic and non-metallic minerals, and coal (we exclude natural gas and oil to be consistent with the patent data). More precisely, I use the following Harmonized System (HS) Codes (1992): 25 – Salt, Sulphur, Earths, Stone, plastering materials, lime and cement; 26 – Ores, Slag and Ash; 2701 – Coal, briquettes, ovoids and similar solid fuels manufactured from coal; 2702 – Lignite, whether or not agglomerated, excluding jet; 2703 – Peat (including peat litter), whether or not agglomerated; 2704 – Coke and semi-coke, of coal, lignite or peat, whether or not agglomerated, retort carbon; 2705 – Coal gas, water gas, producer gas and similar gases, other than petroleum gases and other gaseous hydrocarbons; 2706 – Tar distilled from coal, from lignite peat and other mineral tars, whether or not dehydrated or partially distilled, including reconstituted tars; 2707 – Oils and other products of the distillation of high temperature coal tar; similar products in which the weight of the aromatic constituents exceeds that of the non-aromatic constituents; and 2708 – Pitch and pitch coke, obtained from coal tar or from other mineral tars.

The second aggregate captures data on exports and imports of mining equipment. Mining equipment includes a wide range of equipment used from exploration to smelting operations in the discovery, extraction and processing of coal, minerals and ores (UNCTAD, 2007). The classification used builds upon a selection of HS classifications regarding mining equipment previously made by Bamber, Fernandez-Stark and Gereffi (2016). Details of this selection are presented in appendix A. Following the approach of Bamber, Fernandez-Stark and Gereffi (2016), the equipment used in the mining value chain are divided into four principal categories:

i. Surface and underground mining equipment (SUM) which includes drilling equipment used in exploration activities. SUM also includes equipment involved in extracting the materials

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[16] The development of spin-off industries that are suppliers of services and inputs to mining companies, as well as commodity processing industries is essential for diversification, employment generation, improvement of social capabilities and the overall resilience of the economy (Calzada Olvera and Foster-McGregor, 2018).

from the earth (e.g. continuous miners, dozers, draglines, drills, excavators, loaders, scrapers, shovels, and mining trucks among others).

ii. Mineral processing equipment (MP) includes equipment used to separate the mineral from waste material, remove impurities, or prepare the ores for further refinement (e.g. crushers, cyclones, feeders, flotation cells, grinders/mills, etc.).

iii. Bulk materials handling (MH) includes equipment that is involved in moving ore and waste materials in all stages of the mining operations (e.g. conveyers and wagons).

iv. Wear parts: SUM, MP and MH include components and parts that must be regularly replaced due to abrasion during use. These are low value parts[17] and are referred to as wear parts and include items such as steel balls and liners for grinding mills and liners for dump truck bodies.

Other equipment such as that used in the smelting and refining process or ship-loading is not included within our scope, as this equipment is usually operated off-site or may be used for multiple different sectors. Mining infrastructure is also not included in this chapter.

The second major source of data is the WIPO Mining dataset, which collects information on patents related to mining technologies from all over the world for the period 1970-2015. In particular, the database contains information on patents related to technologies regarding metallic and non-metallic minerals, and coal. Each patent has an application identifier which corresponds to the application identifier in EPO-PATSTAT.

The starting point for building the WIPO Mining Database is the 2017 autumn edition of the European Patent Office's Worldwide Patent Statistical Database (PATSTAT). PATSTAT offers access to over 100 million patent records from more than 90 patent authorities. Patent data from WIPO's patent family database are also used in the construction of the database. These latter data are a combination of the EPO-PATSTAT database[18] and the PCT national phase entries stored in the WIPO Statistics Database (Daly, Valacchi and Raffo, 2019; p. 12).

As regards the search strategy used when constructing the WIPO dataset, WIPO chose to combine keywords found in abstracts and titles, further collecting information in multiple languages. The first step in the process was to create a subset of patents that contained keywords related to mining in the title or abstract. Six categories of keywords were used in five languages (English, German, Spanish, French and Portuguese), the most frequently occurring languages in the abstract and title tables of PATSTAT. The keywords were searched in the titles and abstracts and assigned a general keyword term (see Daly, Valacchi and Raffo (2019; pp. 52-53) for a list of keywords). A second subset of data was extracted by retrieving all patents comprising at least one E21 (Earth or rock drilling; Mining) International Patent Classification (IPC) or Cooperative Patent Classification (CPC) mark. These two subsets of data were used as a subset of the whole PATSTAT database to search within.

The WIPO dataset identifies a unique technology sub-sector and category for each patent record. However, it is not straightforward to assign patents to a single category. When examiners classify patents, they assign classification symbols according to the technological features in patent applications. A patent application that relates to multiple technological features can be assigned to several IPC codes. As a result,

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[17] It is worth stressing that each of the four categories concerning mining equipment reflect the different stages of use in the mining industry and each of them includes equipment with a range of equipment from low to high value.

[18] This link to the PATSTAT database also allows me to obtain data on forward citations used in part of the analysis.

the patents in the mining dataset will inevitably be classified in multiple classes, and therefore multiple mining categories[5].

Some key information contained in the WIPO dataset distinguishes between inventor country of origin, applicant country origin and the office code or application authority of patents. Also included is a variable that indicates in how many offices (countries) that patent has been filed. Since patents are grouped in patent families, a family identification is also included along with information on the size of the family to which the patent belongs.

Patents are further categorized into nine mining subclasses in terms of technology: exploration, blasting, mining (mine operation), processing, metallurgy, refining, transport, automation and environmental (see Daly, Raffo and Valacchi (2019), in particular: Appendix B for details about the search strategy and categorization; Appendix C and table 1 for a description of each mining technological field). These nine mining technological classes were carefully selected thanks to a search strategy made up of a combination of IPC codes and keywords in PATSTAT.

For part of the analysis, I am interested in distinguishing between different types of firms, notably between mining firms (coal, metal ore and non-metallic mineral), Mining Equipment Technology Services (METS) firms, and Oil & Gas and Quarrying. This distinction allows for an examination of the role of suppliers of mining firms (METS), firms that are considered to be key innovators for the mining industry. To do this, I merged the WIPO Mining Database with data from ORBIS. ORBIS is a commercial database from Bureau van Dijk that contains information on more than 120 million companies around the world. These data can be combined with the WIPO Mining Database using a unique firm identifier. ORBIS focuses on the biggest players in the market, which are also the most active ones in terms of research activity.

The final major source of data is the fDi Markets Database, which is an online database provided by fDi Intelligence – a specialist division of Financial Times Ltd – that monitors cross-border investments covering all sectors and countries worldwide from 2003 onwards. fDi Markets is an event-based (or deal-based) database, i.e. each entry is a project, which collects detailed information on announced cross-border greenfield investments[19] (i.e. new wholly-owned subsidiaries, including joint ventures whether they lead to a new physical operation) from several publicly available information sources, including nearly 9000 media sources, over 1000 industry organizations and investment agencies, and data purchased from market research and publication companies. The time span covered by this database covers the period 2003-2018 (for further details regarding fDi Markets dataset see Zanfei, Coveri and Pianta, 2019). For the purposes of this chapter, the main data of interest from the fDi Markets database relate to the Metals, Minerals and Coal, oil and natural gas (in particular Coal mining and Support activities for mining) sectors, though data from other sectors is also used when constructing FDI-based specialization indices.

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[19] One possible limitation of fDi Markets regards the inclusion of greenfield investments only, while it does not cover information on mergers and acquisitions, providing a partial picture of global flows of FDI. However, the importance of mergers and acquisitions should not be over-emphasized. In fact, according to the World Investment Report 2018, over the period 2008-2014 the value (the number) of greenfield FDIs were twice (more than twice) as large as the value (the number) of net cross-border mergers and acquisitions deals (UNCTAD; (2018; pp. 7-8); Zanfei, Coveri and Pianta, 2019). It follows that focusing on greenfield investment allows to capture a large portion of FDI flows, reassuring us about the representativeness of the data we employ.

2.3 Results

The analysis in this chapter focuses on four main issues, as defined above. In the first, I consider whether Latin America is specialized in the production and export of mining products. To address this question, I focus on indicators of revealed comparative advantage to examine whether Latin America has comparative advantage in (exporting) mining products. I also consider alternative data reflecting mining production patterns, by examining whether Latin America has comparative advantage in attracting inward FDI in the mining sector. Secondly, I investigate whether the specialization in producing mineral commodities is associated with the development of production capabilities in upstream activities along the mining value chain, i.e. the production (export) of mining equipment. Moreover, I also consider whether Latin America has comparative advantage in importing (using) such mining equipment from abroad. Thirdly, and relatedly, this paper examines whether a similar specialisation pattern is also observed when using patent data to examine whether Latin America is specialised in the production of mining knowledge (i.e. innovation). Fourthly, the quality of mining innovation carried out in Latin America is examined. Specifically, we compute a revealed technological advantage concerning a set of leading-edge mining technologies, which are useful to solve important issues for the mining industry. Relatedly, we also examine the quality of the Latin American mining patents using patent value indicators.

The results section addresses each of these issues in turn, with Section 3.1 reporting results on Latin America's specialization in mining products, Section 3.2 considers whether Latin America is specialized in mining equipment, Section 3.3 examines whether Latin America is specialized in producing mining innovation and Section 3.4 investigates the quality of innovation in the Latin American mining sector.

2.3.1 Latin America's Trade Specialization in Mining Products

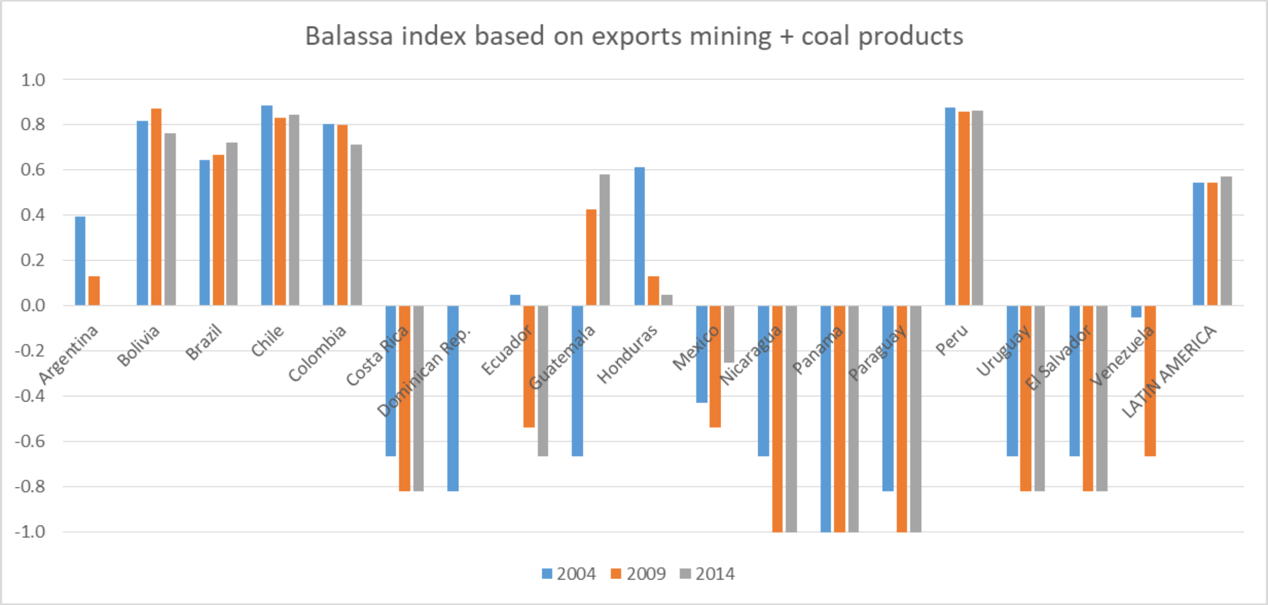
To examine the export specialization patterns of Latin America, I use the commonly used Balassa index (Balassa, 1965) of Revealed Comparative Advantage (RCA). This index compares the importance of a product or sector in a country's export basket to that of a comparison group (usually world exports). If the country is observed to export a higher share of a particular product or industry than the world as a whole, then it is concluded that the country has a revealed comparative advantage in the export of that product or industry. The RCA of exports (X) for industry i in economy k is thus computed as:

$$RCA_k^i = \frac{X_k^i \Big/ \sum_k X_k^i}{\sum_i X_k^i \Big/ \sum_k \sum_i X_k^i}$$

If the RCA is greater than one, the economy is considered to be specialized in the export of the particular product or industry. In the analysis below, I follow Foster-McGregor, Nomaler and Verspagen (2019) in transforming the RCA values as $(RCA - 1)/(RCA + 1)$, which makes the figures appear more symmetric. As a result of this transformation, a value of the RCA index above zero corresponds to a country having revealed comparative advantage in the export of the product.

Using the definition of mining products discussed in the previous section and data from UN Comtrade, Figure 1 reports information on the RCA for a selection of Latin American countries (as well as a Latin America aggregate) for three different years (2004, 2009 and 2014). This allows for a comparison both across countries and across time. The results reported in Figure 1 indicate that Latin America as a whole was specialized in exporting mining products from 2004 to 2014[20]. The RCA index rose slightly from 0.5 to 0.6 between 2009 and 2014, suggesting an increasing dependence on natural resources. Considering individual countries, the results indicate that Bolivia, Brazil, Chile, Colombia and Peru have a strong specialization in mining exports with a value of the RCA index often exceeding 0.6. Guatemala and Honduras are also found to be specialized in the exportation of mining products, albeit with differing trends, with Guatemala obtaining and increasing its specialization in mining products over time and Honduras beginning the period with a strong specialization that steadily declines. The rising trend observed in Guatemala is also found in Brazil, while a declining trend is observed in Bolivia and Colombia. The remaining countries in the sample (i.e. Costa Rica, Dominican Republic, Mexico, Nicaragua, Panama, Paraguay, Uruguay, El Salvador and Venezuela) are not found to be specialized in exporting mineral commodities during the time span under study.

Figure 1 – RCA based on export data of mineral commodities for Latin American countries



Note: The RCA variable is transformed such that it lies between -1 and +1, with values greater than zero indicating RCA.

Source: Own elaboration based on UNCOMTRADE database.

The results presented in Figure 1 suggest that Latin America has a specialization in the export of mining commodities, but a remarkable heterogeneity exists across Latin American countries. In particular, the overall specialization of the continent is driven by a subset of Latin American countries (i.e. Argentina, Bolivia, Brazil, Chile, Colombia, Guatemala, Honduras and Peru). This specialization pattern observed

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[20] This is in line with Cimoli and Porcile (2011) who state that, in Latin America, sectors intensive in natural resources and raw labour have generally had a dominant position in exports. Structural change and diversification were remarkably slow compared to those countries that succeeded in catching up, particularly the Asian countries.

in exports, can also be found when considering alternative data that may reflect production patterns. In particular, a similar pattern is found when considering data on inward FDI flows into Latin American countries.

Mineral production characteristically lends itself to transnational activity. FDI has historically played a key role in enabling exploration and extraction activities worldwide, with MNEs their ultimate orchestrators. According to a recent survey regarding the 100 largest (publicly-listed) mining corporations, 70% are MNEs and over one half of their subsidiaries are foreign-owned (60%). Not only are large mining companies predominantly transnational, but they are more prolific in developing countries than are large MNEs in other industries. Some 35% of foreign affiliates of mining MNEs in UNCTAD's ranking of the top 100 global MNEs are located in developing countries (Formenti and Casella, 2019).

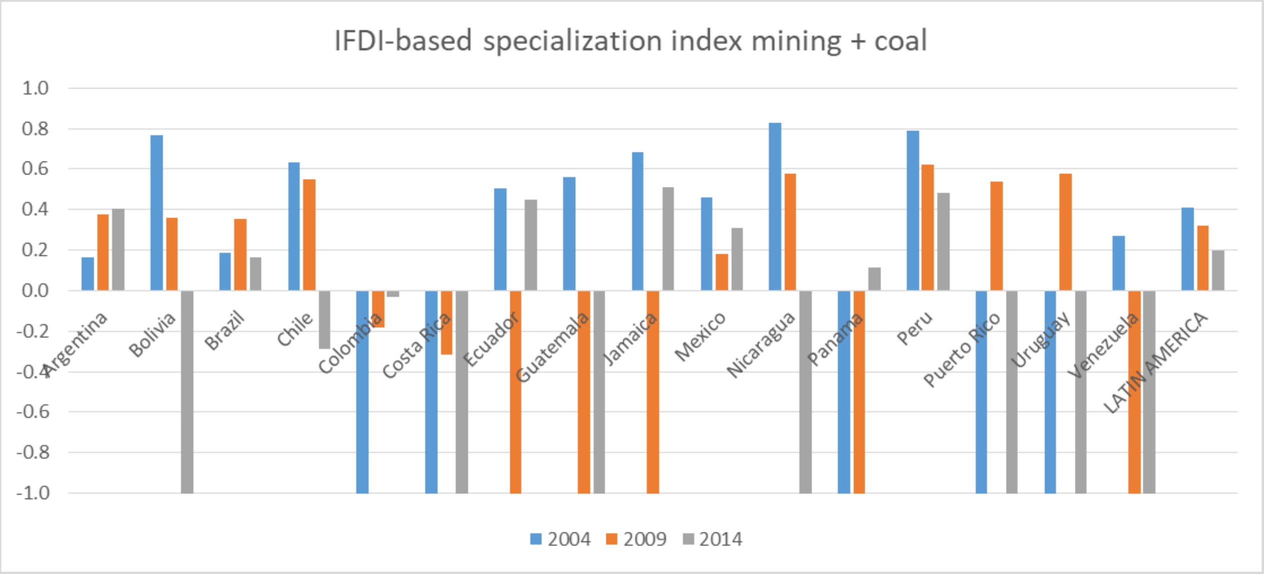
To examine the importance of inward FDI in the mining sector of Latin America, I follow a similar approach to above and construct an FDI-based specialization index (Zanfei, Coveri and Pianta, 2019) by adjusting the RCA indicator defined above. The new indicator is constructed as:

$$RCA_k^i = \frac{IFDI_k^i \big/ \sum_k IFDI_k^i}{\sum_i IFDI_k^i \big/ \sum_k \sum_i IFDI_k^i}$$

with IFDI referring to inward FDI. This is analogous to the RCA indicator constructed using export data, with Zanfei, Coveri and Pianta (2019) stating that the FDI specialization indices are computed in a given industry for a given economy as the share of IFDIs (Inward Foreign Direct Investments) drawn in that industry by such economy over the share of total inward FDIs attracted by such economy in all industries worldwide. As with the export-based RCA, I transform the variable such that values greater than zero indicate specialization.

Having a mining FDI specialization indicates that a country has the ability to attract FDI in mining that is greater than other areas, which in turn may have a substantial effect on the host economy in terms of structural change, agglomeration economies and potential technological spillovers accruing to local firms and institutions, for example (Antonietti et al., 2015; Baldwin and Venables, 2013). Figure 2 reports the results of the FDI specialization index for a set of Latin American countries and for Latin America as a whole.

Figure 2 – Inward FDI-based Specialization Index[21] based on number of IFDI projects concerning the mining sector for Latin America



Note: consistent with Figure 1, we transform the RCA variable based on IFDI such that it lies between -1 and +1, with values greater than zero indicating RCA.

Source: Own elaboration based on fDi Markets database.

Figure 2 indicates that Latin America as a whole is specialized in attracting FDI in the mining sector, although the extent of this specialization is declining over time. This is also true for many of the individual countries. From 2009 to 2014, for example, Brazil, Chile and Peru saw a decline in their specialization in mining FDI. Conversely, in other countries – such as Argentina, Ecuador, Jamaica, Mexico and Panama – specialization in mining FDI increased, particularly in the latter period. Only two of the countries considered (Colombia and Costa Rica) were not found to be specialized in mining in the period considered.

To summarize, Latin America is specialized in the production and export of mining products and in attracting inward FDI into the mining sector. However, the data show a high heterogeneity across countries and FDI-based specialization appears to be declining in many countries. This specialization pattern in attracting FDI can offer both advantages and disadvantages, being a source of technology but also potentially substituting for own production of technology. In the mining industry, for example, the hunt for mineral resources has historically been the main driver of FDI, leaving little room to manoeuvre for knowledge transfers and technological catch-up. In the following sections, I consider whether this

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[21] We rely on the number of FDI projects rather than on the value of capital involved, since criteria for value estimation of capital investment are not made explicit by fDi Markets. In addition, we follow Crescenzi et al. (2015, p. 33) holding that often the number of investment decisions in a given geographical destination (in our case Latin America) is likely to be a more proper unit of analysis than the value of the project insofar as such decisions have been demonstrated to be broadly independent from the amount of capital invested (Amighini et al., 2014). Zanfei, Coveri and Pianta (2019; p. 5) also stress the fact that a number of empirical works using fDi Markets have been performed exploiting the number of FDI projects rather than the data on capital investment.

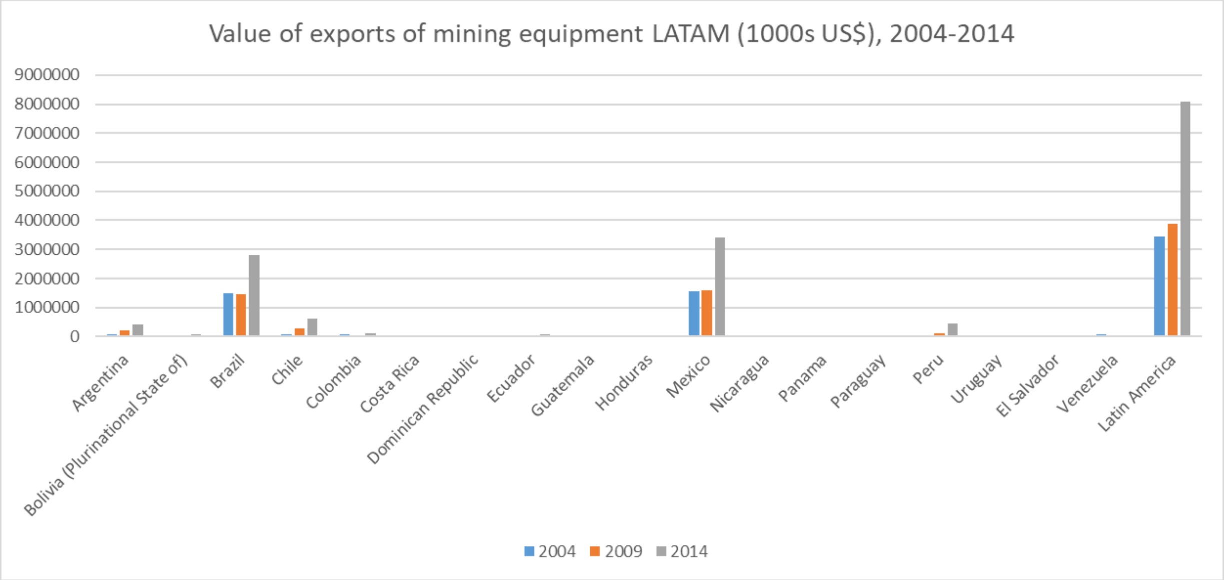
specialization in the production of mining products is associated with activity in higher value-added mining activities, namely mining equipment and mining innovation.

2.3.2 Latin America's Specialization in Mining Equipment

In this section, I examine whether Latin America has been able to develop specialization in the production of mining equipment. Given that Latin America has developed a specialization in the production of mining products, it may be that it has also been able to develop specialization in upstream activities associated with this specialization, activities that may include the production of mining equipment. At the same time, it may also be that Latin America's specialization in mining products has been driven by the importation of mining equipment, possibly through inward FDI and the activities of TNCs.

Figure 3 reports the value of exports of mining equipment between 2004 and 2014. As already mentioned in the data description section, we follow Bamber, Fernandez-Stark and Gereffi (2016) in defining mining equipment. The figure indicates that after remaining relatively stable between 2004 and 2009, there was a rapid rise in the export of mining equipment between 2009 and 2014 for Latin America as a whole. The export of mining equipment in Latin America is driven by two of the largest countries – Brazil and Mexico – with Argentina, Mexico and Peru also having significant levels of mining equipment exports. All of these countries witnessed an increase in the value of mining exports over time, with the increase being most pronounced in Mexico[22].

Figure 3 – Export values (1000s US$) of mining equipment in Latin America, 2004-2014



Source: Own elaboration based on UNCOMTRADE database.

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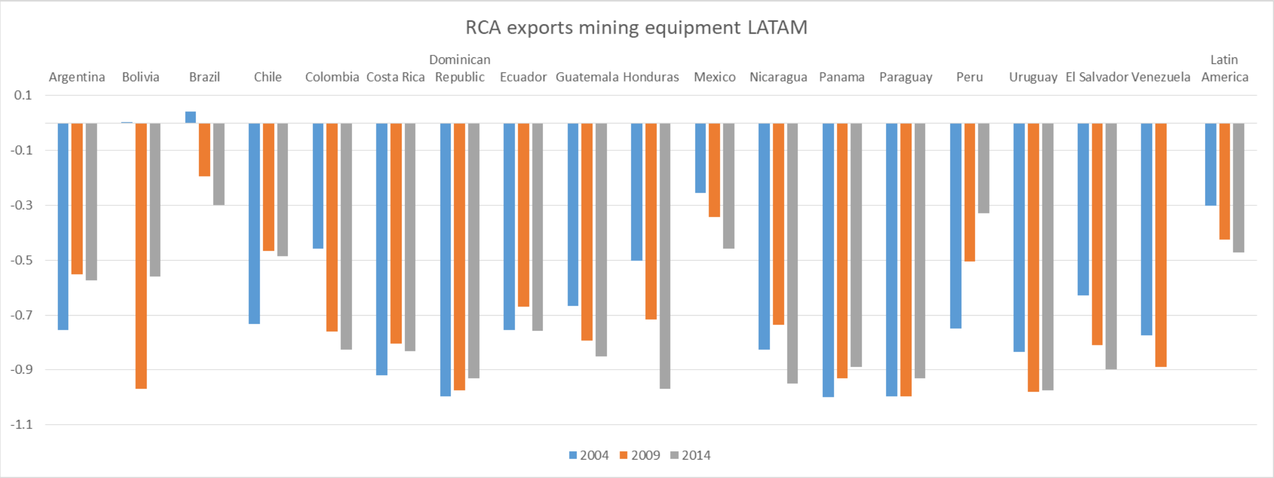
[22] Export data are all in current US$, meaning that price changes are also likely to play a role in driving these developments over time.

Moving beyond the level of exports, I further consider whether Latin America has a comparative advantage in the export of mining equipment using the same approach of calculating the RCA as above. The major difference between the approach above and that here is that I no longer consider industries when constructing the RCA variable, but instead products. The set of products considered includes all traded products, so that we calculate specialization in the export of mining equipment relative to all traded products. Results of these calculations are reported in Figure 4.

Figure 4 – RCA based on export data (US$) regarding mining equipment for Latin America over time, 2004-2014



Note: Consistent with Section 3.1, we transform the RCA variable based on export of mining equipment such that it lies between -1 and +1, with values greater than zero indicating RCA.

Source: Own elaboration based on UNCOMTRADE database.

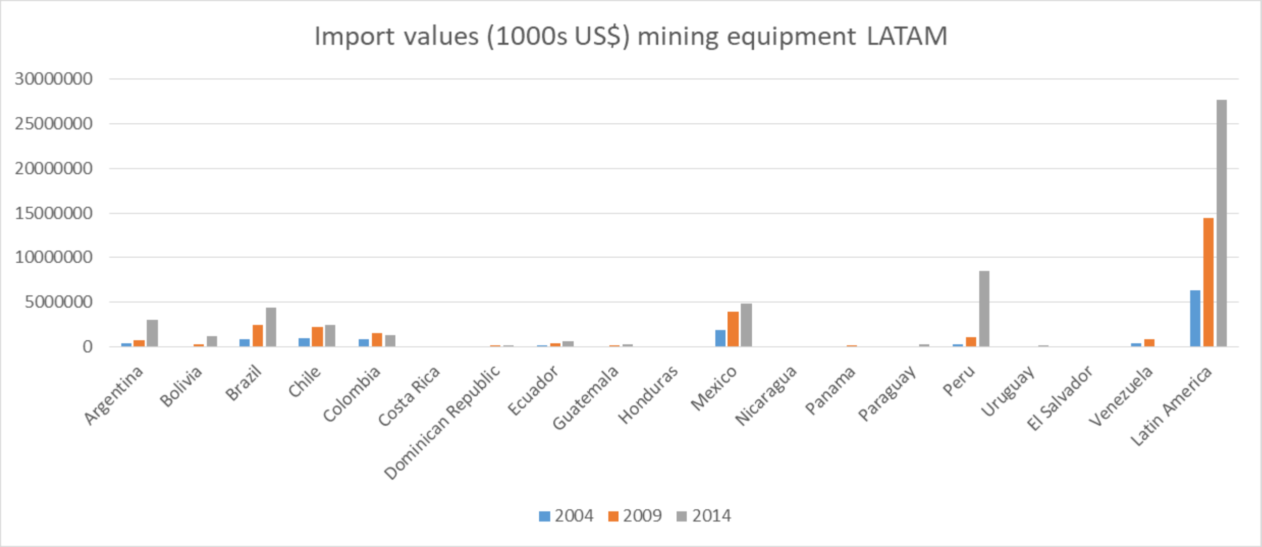
The results in Figure 4 suggest that Latin America is not specialized in exporting mining equipment in any of the three periods under consideration, with the observed comparative disadvantage in exporting mining equipment actually increasing over time (as represented by the declining RCA values from -0.3 in 2004 to -0.5 in 2014). With the exception of Brazil in the initial period, the results further suggest that none of the individual countries in Latin America has a comparative advantage in the export of mining equipment, with the observed comparative disadvantage increasing over time in many of the countries considered. Such a result may indicate the lack of local METS firms in Latin America, something that I return to later in the paper.

Given the importance of mining production for the Latin American economy and given the lack of comparative advantage in the production of mining equipment, it should be expected that Latin America is relatively specialized in the importation of mining equipment. This is confirmed by figures 5 and 6 which report the value of imports of mining equipment (Figure 5) and the indicator of revealed comparative advantage of imports of mining equipment (Figure 6).

Figure 5 shows that there was a relatively rapid increase in the import of these mining technologies in Latin America between 2004 and 2014[23]. If we analyse individual Latin American countries, we observe that Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Mexico, Paraguay and Peru increased their import of mining equipment in terms of absolute values between 2004 to 2014. Perhaps of more importance, Figure 6 indicates that Latin America as a whole is specialized in importing mining equipment[24], with the comparative advantage increasing between 2004 and 2009, but falling slightly between 2009 and 2014. Most Latin American countries are specialized in the import of mining equipment, with Argentina, Bolivia and Peru, among others, also seeing an increase in specialization over time. Countries that are not specialized (or have seen a decline in specialization such that they were not specialized at the end of the period) in importing mining equipment include Costa Rica, Guatemala, Honduras, Nicaragua, Uruguay and El Salvador.

To summarize, despite being specialized in the extraction and export of mining products Latin America does not have a specialization in the production and export of mining equipment, instead relying on the importation of mining equipment to meet the needs of the sector. In other words, Latin America relies on the diffusion of technology embodied in imported mining equipment, rather than relying on its own technology. In the following subsection, I ask whether this may be reflective of the lack of innovation in the mining sector in Latin America.

Figure 5 – Import values (1000s US$) of mining equipment in Latin America, 2004-2014



Source: Own elaboration based on UNCOMTRADE database.

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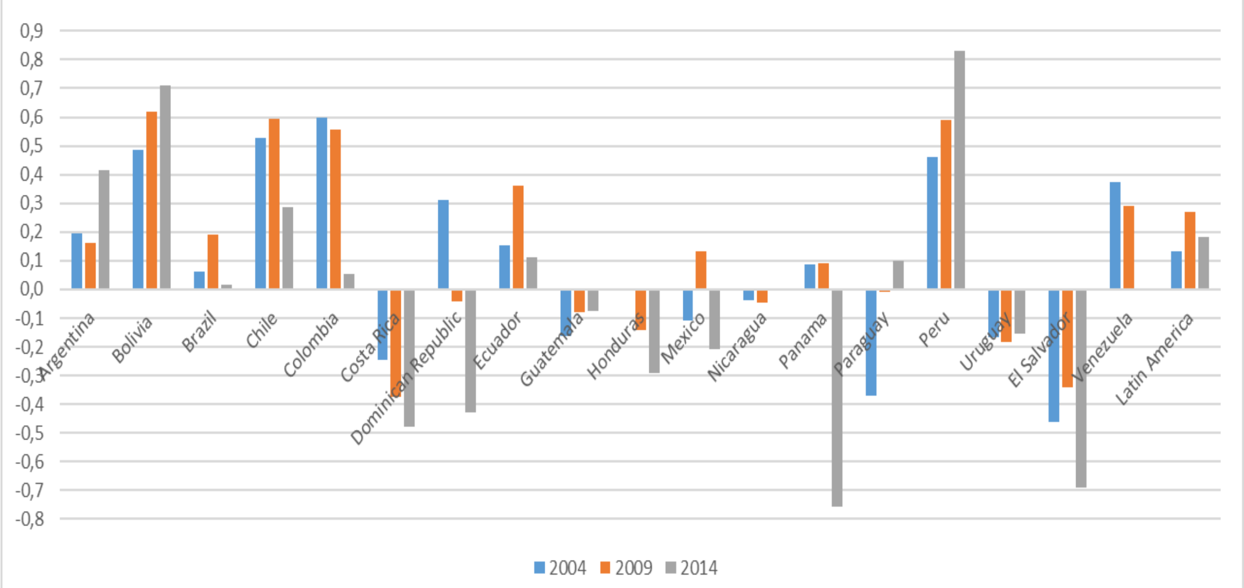
[23] It can mean that there was a more intensive use of them. Nevertheless, given that both import and export values jumped between 2004 and 2014, it may also suggest that the price of mining equipment increased rapidly.

[24] It must be stressed that surface and underground mining equipment and mineral processing equipment represent the overwhelming majority of mining equipment (see Bamber, Fernandez-Stark and Gereffi, 2016).

Figure 6 – RCA based on import data (US$) regarding mining equipment for Latin America over time, 2004-2014



Note: Consistent with Section 3.1, we transform the RCA variable based on import of mining equipment such that it lies between -1 and +1, with values greater than zero indicating RCA.

Source: Own elaboration on UNCOMTRADE database.

2.3.3 Latin America's Specialization in Mining Innovation

To examine whether Latin America has a specialization in mining innovation or not, I follow a similar approach to above by constructing an indicator of revealed technological advantage (RTA) similar to the RCA variables defined above. In particular, I follow Le Bas and Sierra (2002) who used the index of RTA originally developed by Soete (1987) to measure the relative technological strength of a country in a certain industry. The RTA index can be defined for countries in a certain technological field, which in my case is mining. The index of RTA can be calculated as:

$$RTA_k^i = \frac{P_k^i / \sum_k P_k^i}{\sum_i P_k^i / \sum_k \sum_i P_k^i}$$

Where P_k^i is the number of patents applied for by applicants in industry i in economy k. As above, I transform this variable such that numbers greater than 0 indicate that a country has an RTA in mining innovation.

In order to construct this indicator, I require information on the production of mining technologies, for which I use information from patent data (i.e., the country of residence of the applicant[25]). This indicator

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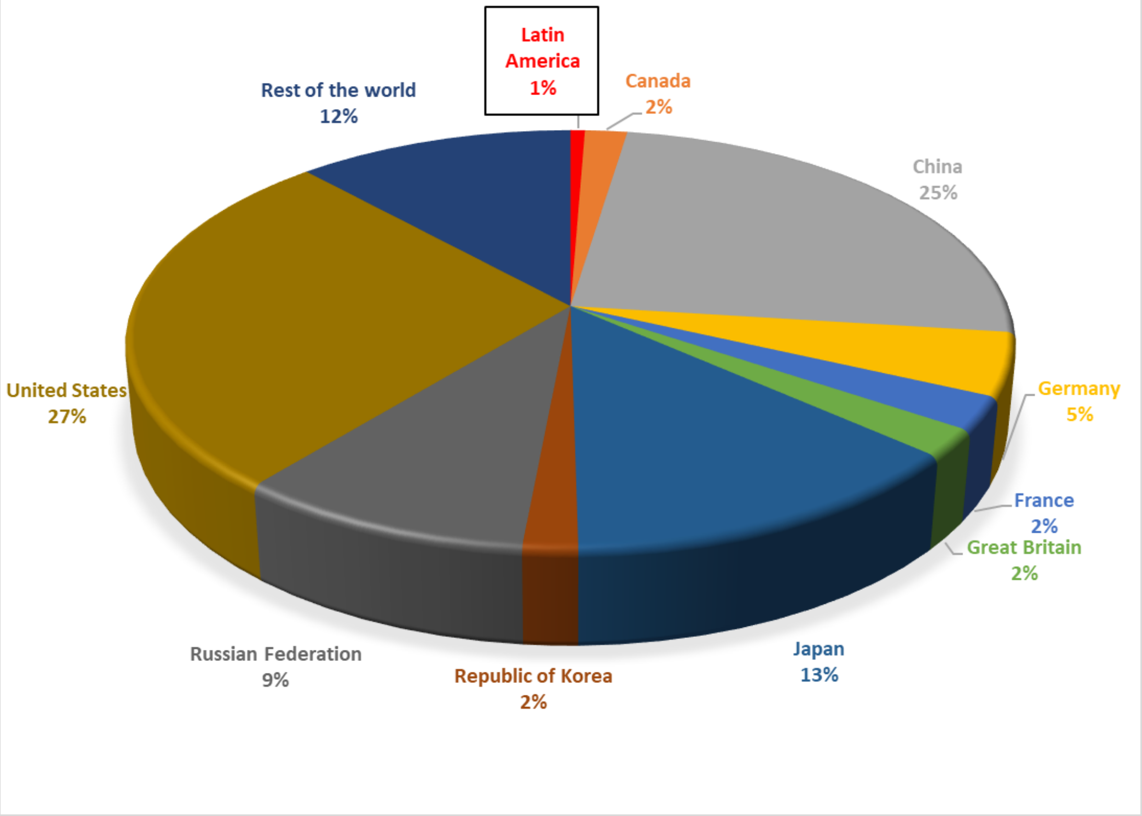
[25] Precisely, this is a count of the number of patent applications taken out everywhere.

is informative about the knowledge created locally at the country level and where mining innovation activities take place (OECD, 2009). Before presenting results of the RTA in mining for Latin American countries, I report in Figure 7 the distribution of the applicants (in terms of number of patent applications) concerning mining patents at the global level for the period 1970-2015.[26]

The results presented in Figure 7 indicate that patenting in mining is dominated by the USA and China. These two countries account for 52% of mining patents considering applicants origin. Other countries that account for a relatively high share of patents include Russia, Japan and Germany. Conversely, the whole of the Latin American region accounts for around 1% of global mining patents, providing some initial evidence that Latin America is not heavily engaged in mining innovation. In data not reported in the figure, we further observe that mining patents are unevenly distributed across the countries of Latin America, with more than 75% of Latin American patents being invented in just three (Brazil, Chile and Mexico) of the 18 Latin American countries.

Figure 7 – Share of mining patents in terms of applicant's country of origin worldwide, 1970-2015



Note:

- LATAM does not include Haiti, Paraguay, Puerto Rico, Guadeloupe, French Guiana, Saint Martin and Saint Barthelemy because they have no mining patents in terms of applicant country.
- "Rest of the world" represents all the other countries, that are not labelled in the chart, with less than 1 percent each.
- We use counts of patent applications to make these statistics.

Source: own elaboration based on WIPO Mining Database.

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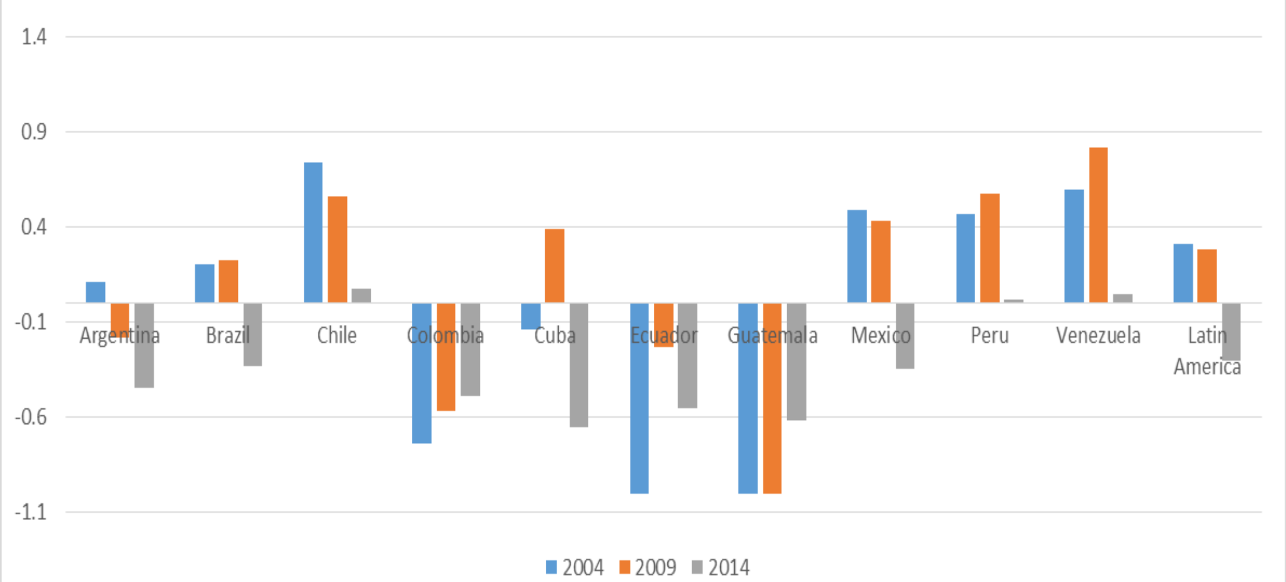
[26] Figure B1 in Appendix B presents complementary evidence on the country of origin of the inventor, i.e. the individual who carried out the inventive activity.

Turning to the data on RTAs for Latin America, Figure 8 reports information for 10[27] Latin American countries for the same three years as above (i.e., 2004, 2009, 2014). The figure reveals that Latin America as a whole had an RTA in mining innovation in 2004, but that this technological advantage declined over time such that by 2014 it had a technological disadvantage. In terms of individual countries, we observe that 6 out of the 10 countries had an RTA in mining in the initial period. Those countries that didn't have an RTA (Colombia, Cuba, Ecuador, Guatemala) in the initial period were generally not able to develop an RTA as time went by. The remaining countries had an RTA in 2004, but either lost that advantage by 2014 (Argentina, Brazil, Mexico) or saw it diminished (Chile, Peru, Venezuela). Overall, therefore, the results suggest a weakening performance of Latin America in mining innovation.

Figure 8 – RTA in mining technologies per each Latin American country over time, in terms of origin*, 2004-2014



*"origin" is the country of residence of the applicant.

Note: consistent with the previous sections, we transform the RTA variable based on patents such that it lies between -1 and +1, with values greater than zero indicating RTA.

Source: Own elaboration based on WIPO Mining Database and WIPO IP Statistics Data Centre for data regarding patents in all sectors worldwide (https://www3.wipo.int/ipstats/index.htm?tab=patent).

For purposes of comparison, I compare results in terms of RTA for Latin America with those for applicants originating in countries that represent the global technological frontier in mining, i.e., Australia, Canada, China, Germany, France, the UK, Japan, the Republic of Korea, Russia and the US. For the sake of accuracy, the countries on the global mining technological frontier have been selected based on Figure

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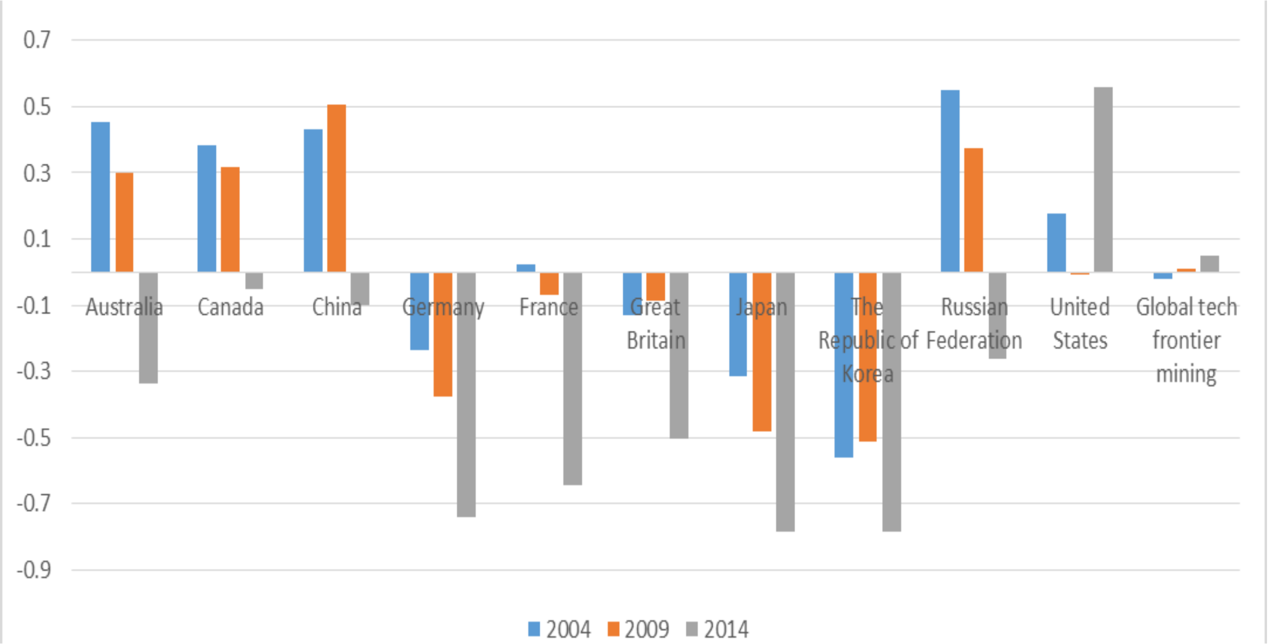
[27] These are the Latin American countries for which the mining patent data and the patent data for all sectors worldwide (useful to construct the RTA indicator) are available. In this context, we are able to include also Cuba for which there were missing data concerning mining equipment and mineral commodities.

7, i.e. the countries that have a higher number of mining patents invented locally at the global level[28]. Results for the frontier are reported in Figure 9.

Figure 9 – RTA in mining technologies per each country at the global technological frontier in mining in terms of origin*, 2004-2014



*"origin" is the country of residence of the applicant.

Note: consistent with the previous sections, we transform the RTA variable based on patents such that it lies between -1 and +1, with values greater than zero indicating RTA.

Source: Own elaboration on WIPO Mining Database and WIPO IP Statistics Data Center for data regarding patents in all sectors worldwide (https://www3.wipo.int/ipstats/index.htm?tab=patent).

The results in Figure 9 indicate that the countries at the global technological frontier didn't have an RTA in mining technologies in 2004, but developed a specialization over time that further increased between 2009 and 2014. This (slight) increasing trend is largely due to the increase in the RTA values of the US, however. In fact, the other countries witnessed a decline in the RTA between 2009 to 2014, with no other country having a specialization in mining innovation in 2014. That this set of countries (with the exception of the US) saw declines in RTA over time, such that they had no RTA by 2014, partly reflects the fact that they tend to be diversified economies with specialization in other sectors. The results are also consistent with those reported for Latin America, with nearly all Latin American countries witnessing a declining RTA over time also.

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[28] It is worth emphasizing that, when considering the global technological frontier, we refer to the number of patents, but not to specialisation in terms of revealed technological advantage. This definition of global mining technological frontier will also hold in the rest of the paper.

The fact that Latin America could have an RTA in mining innovation in the earlier period, but not be specialized in the production and export of mining equipment may indicate that its specialization was in particular parts of the mining process. In the following section, I examine this further.

2.3.4 The Quality of Latin America's Mining Innovations

This section examines the quality of local mining innovation in Latin America by considering two different and complementary tools, i.e. the specialization on cutting-edge (key) mining technologies (Section 3.4.1) and the quality of the mining patents invented by Latin American applicants through patent value indicators, moving beyond patent counts (Section 3.4.2). Patent value indicators are aimed at detecting whether a patent fulfils the key objectives of the patent system, i.e. to reward and incentivise innovation while enabling diffusion and further technological developments (Guellec and van Pottelsberghe de la Potterie, 2007).

2.3.4.1 Latin America's Specialization in Key Mining Technologies

In this section, I consider a group of key mining technologies that are essential to solve important issues for the mining industry, examining whether Latin America has been able to develop specialization in these particular fields. This is also a proxy for investigating the quality of the Latin American mining innovation. In addition, I compare the specialization in key mining technologies of Latin America to countries on the global mining technological frontier to examine whether the specialization patterns of both group of countries are moving towards (convergence) or away (divergence) from each other[29]. They regard three specific mining technological fields: environmental, exploration and transport innovations.

The first technology field I consider is exploration technology, which is a costly, risky and delicate phase in mining activities both for local communities and for companies, especially in developing countries (Calzada Olvera and Iizuka, 2020). A mineral exploration property is defined as a tenement or group of tenements that are at the early to intermediate stages of mineral exploration (i.e. prior to pre-feasibility) and without the prospect of any reasonably certain future mine production and cash flows. The average probability of success in mineral exploration is so low, and the attendant geological uncertainty so high that it has often been difficult for investors, managers and exploration geoscientists to actively manage for financial success (Eggert, 1993; Leveille and Doggett, 2006; Kreuzer and Etheridge, 2010). This uncertainty relates to: (i) inherent natural variability of geological objects and processes, which is a property of nature and exists independent of our geological investigations (Kreuzer and Etheridge, 2010); (ii) conceptual and modern uncertainty (McCuaig, Kreuzer and Brown, 2007), which is linked to our incomplete knowledge and subjective interpretation of geological objects and processes (Welsh et al., 2005); and (iii) errors that occur when we sample, observe, measure or mathematically evaluate geological data, and the propagation of these errors.

Calzada Olvera (2021) states that, in the particular case of the mining industry, the main innovation driver for mining firms is the reduction of operational costs. Based on four surveys conducted among mining

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[29] It is worth remembering that, with the notion of global mining technological frontier, we consider the countries which have the highest share of mining patents invented locally at the global level (see Figure 7). Therefore, when considering the frontier, we refer to number of patents, but not specialisation in terms of RTA. This holds even in the rest of the paper.

firms in Canada, Australia, South Africa and Latin America, the top six inducements for innovation are (in this order of priority): (i) reducing costs to operate; (ii) reducing risk; (iii) safety; (iv) improved asset productivity; (v) reducing costs to develop assets (new mines); and (vi) improving sustainability and reducing environmental footprint in Latin America (Deloitte, 2015). Exploration mining innovations fit well in addressing these issues. In effect, Calzada Olvera (2021) argues that exploration is considered one of the riskiest stages of the supply chain[30], considering that it involves heavy investments (mostly from drilling), the use of high-technology equipment and very highly skilled labour and services.

The second technology field I consider is environmental technology. Mining activities have intense socio-economic and environmental impacts on local and regional communities. As the mines are usually located in sparsely populated regions, the large-scale operation of mining activities can create both positive and negative disruptions (Katz and Pietrobelli, 2018). The absence of appropriate regulatory measures, policies and especially institutional capabilities may cause negative impacts for the local society. Iizuka, Pietrobelli and Vargas (2019; p.7) state that this may subsequently hamper the sustainable operation of the mine. Conversely, mining activities can generate positive outcomes insofar as they are coordinated and well-integrated into the local and regional economies.

Additional demands for innovation come from the social and environmental challenges faced by mining companies. Local communities are concerned with livelihood security, environmental degradation and the perception that the wealth created is not fairly shared. Governments react by introducing more stringent environmental regulations and requiring some local involvement in decision making (Katz and Pietrobelli, 2018), which raises the demand for innovative solutions and sustainable methods of production.

Andersen and Noailly (2019) state that the extraction and processing of metals (e.g., copper, gold, aluminium, iron, nickel), solid fuel minerals (coal, uranium), industrial minerals (phosphate, gypsum) and construction materials (stone, sand and gravel) is associated with air pollution, water contamination by toxic chemicals, landscape disruption and waste generation. Innovation in clean technologies, i.e., technologies aiming to reduce the environmental impact of mining operations, can provide an effective solution to address these environmental challenges. Innovative technologies can help to reduce water and energy consumption, to limit waste production and to prevent soil, water and air pollution at mine sites. Examples of such technologies are water-saving devices, electric haul tracks, desulphurization techniques to limit SO2 emissions and underground mining technologies to minimize land disruption (Hilson, 2002).

Clean technologies are characterized by a "double externality" (Jaffe, Newell and Stavins, 2005): first, just like all technologies, clean technologies generate knowledge spillovers (the knowledge externality) and second, they contribute to reducing the negative externality of pollution (the environmental externality). Due to this dual market failure, firms have little incentives to invest in clean technologies in the absence of government intervention and public policies are always justified to encourage the development of those technologies.

Based on this understanding, current location-specific challenges for mining in Latin America, such as efficient water use, among others, can be considered as an opportunity for innovation with potentially

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[30] The exploration phase is at the start of the mining value chain and lays the foundation for the next stages (Daly, Valacchi and Raffo, 2019).

wider scope for technological and productive development with positive externalities for other industries and even to the society (Fundacion Chile, 2014).

The final technology field I consider relates to transport technologies. As industrialization spreads geographically and higher quality resources are discovered remote from the main markets, the importance of transport in the logistics chain of getting raw materials to downstream users increased. This also triggered the need to innovate in the transport sector with the aim of making mining locations that are more remote, more accessible. Transport has thus become the enabler for a number of mining products to be used on a much wider scale, with the development of the iron ore deposits of Western Australia and of the Amazon region largely a result of improvements in land-based and shipping transportation, for example. Transport technologies are also useful to facilitate backward and forward linkages (Hirschmann, 1977) between mining companies and third parties such as suppliers to mining firms (Molina, Olivari and Pietrobelli, 2016).

Issues of transport technology are important in the context of Latin America. Mining activities are performed at high altitudes and in narrow veins in several areas of Latin America (e.g. Peru and Chile). The La Rinaconda mine, in Puno, at 5100 m above sea level, is the highest in the world (Molina, Olivari and Pietrobelli, 2016) and similar conditions prevail in Chile. Existing equipment and solutions underperform, and there is a need to adapt them or develop new ones. Similarly, in Brazil most of the activity has been moved to deeper mines, where the treatment of the mineral is more complex (Figueiredo and Piana, 2016). These conditions pose remarkable demands for innovation, especially in transport technologies also aimed at removing geographical barriers (Calzada Olvera, 2021; Pietrobelli, Marin and Olivari, 2018).

Given the importance of these three technological fields, I examine whether Latin America has been able to develop an RTA in these technologies, with the results reported in Figure 10. The figure reveals that Latin America as a whole had an RTA in key mining technologies in 2004 and 2009, but that this advantage disappeared by 2014. Such results are consistent with those for innovation in the mining sector more generally (see Figure 8). Considering individual Latin American countries, Colombia, Ecuador and Guatemala are not specialized in key mining innovations in the whole period under study. Argentina, Chile, Mexico, Peru and Venezuela had a RTA in these key technologies in the earlier periods, but as for Latin America as a whole, this advantage disappeared by 2014, such that none of the Latin American countries had a positive RTA in the latter period. In addition to what comes out in Figure 8, Figure 10 also reveals a worsening trend of the cutting-edge (key) technologies[31] in the Latin American mining industry.

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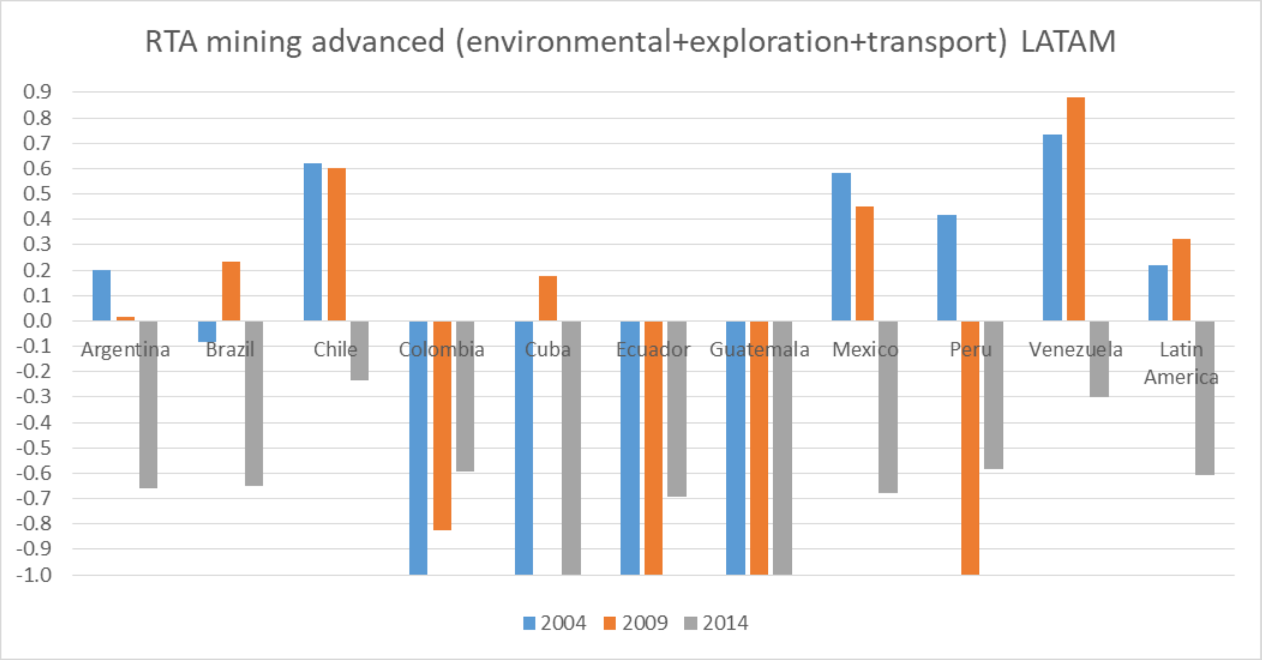
[31] In this context, it is worth remembering that cutting-edge technologies are capturing innovation quality, which is a different measure of quality from that of patent value indicators in Section 3.4.2.

Figure 10 – RTA in key mining technologies (environmental + exploration + transport patents) in terms of origin* in Latin America, 2004-2014



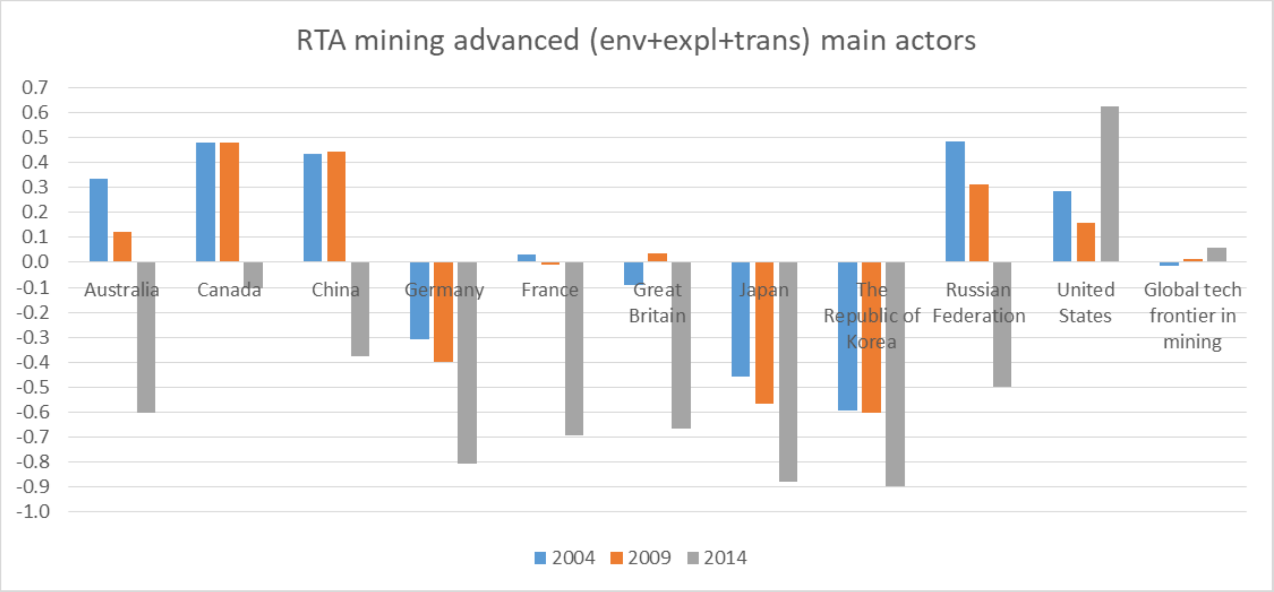
*"origin" is the country of residence of the applicant.

Note: consistent with Figures 8 and 9, we transform the RTA variable based on patents such that it lies between -1 and +1, with values greater than zero indicating RTA.

Source: Own elaboration based on WIPO Mining Database and WIPO IP Statistics Data Center for data regarding patents in all sectors worldwide (https://www3.wipo.int/ipstats/index.htm?tab=patent).

For purposes of comparison, Figure 11 displays information on RTAs in key mining technologies for countries that are generally considered to be on the global mining technological frontier. The figure indicates that this set of countries as a whole did not have an RTA in key mining technologies in 2004, although they became specialized in innovation in these technological fields by 2009, an advantage that they increased slightly between 2009 and 2014. The positive developments over time tend to be due to increases in RTA for a relatively small set of countries, with the slight rise between 2009 and 2014 being largely driven by the increase in the RTA for the US. It is also the case that many of the countries that are considered on the technological frontier do not have an RTA in key mining technologies, revealing that these countries are not involved in medium-high quality mining innovation. Comparing the results for the frontier with those from Latin America (Figure 10) suggests both a converging and a diverging specialization pattern, with convergence taking place in the earlier period (i.e. Latin America's RTA declining and that of the frontier rising) but diverging in the latter period (i.e. Latin America losing RTA in key mining technologies and the frontier increasing its specialization).

Figure 11 – RTA in key mining technologies (environmental + exploration + transport patents) in terms of origin* for countries on the global technological frontier in mining, 2004-2014



*"origin" is the country of residence of the applicant.

Note: consistent with Figure 10, we transform the RTA variable based on patents such that it lies between -1 and +1, with values greater than zero indicating RTA.

Source: Own elaboration based on WIPO Mining Database and WIPO IP Statistics Data Center for data regarding patents in all sectors worldwide (https://www3.wipo.int/ipstats/index.htm?tab=patent).

2.3.4.2 The Quality of the Latin American Mining Patents

The previous section indicated that while Latin America had a technological advantage in mining technologies in the earlier period, this advantage has diminished over time. Beyond considering the specialization pattern, however, it is also important to understand whether the knowledge being developed in the context of Latin American mining is of high quality. I further address this question in this section using information on patent families and patent citations.

For economists, a high-quality patent is generally one that fulfils the key objectives of the patent system, i.e. to reward and incentivize innovation while enabling diffusion and further technological developments (see Guellec and van Pottelsberghe de la Potterie, 2007, for a discussion). Squicciarini, Dernis and Criscuolo (2013) argue that low patent quality is widely perceived to generate uncertainty, to lower incentives to innovate, to stifle technology development and to trigger a number of market failures that ultimately harm innovation, entrepreneurship, employment and growth, as well as consumers' welfare (Hall et al., 2003).

In my analysis, I calculate two patent value indicators for Latin America, further using information on countries at the global mining technological frontier for purposes of comparison. These two indicators of patent quality are an index of patent family size and an indicator based on forward citations (OECD, 2009).

The set of patents filed in several countries which are related to each other by one or several common priority filings is generally known as a patent family. (OECD, 2009; Squicciarini, Dernis and Criscuolo, 2013). In this context, the size of patent families is proxied by the number of patent offices at which a given invention has been protected. Martinez (2010) states that it is now widely recognized that patent families can be used for many purposes, such as to analyse patenting strategies of applicants and countries, monitor the globalization of inventions and study the inventive performance of technological knowledge of different countries.

Patent family data have been used to set an economic threshold, with the aim to capture only the most valuable ones. Since filing patent applications abroad is associated with higher costs for the applicant, in terms of patent office fees, patent attorneys bills and transaction costs, the intuition goes that applicants would only follow the path if the time, effort and cost associated with it, is worth it. Applicants would only seek international patent protection for their most valuable patents, as they would only be willing to do it if the expected commercial value of their invention is high enough. Thus, the higher the size of a patent family to which a patent belongs to, the higher the quality of that patent.

An alternative quality indicator relies on so-called forward patent citations. If a patent[32] is granted, a public document is created containing extensive information about the inventor, his/her employer, and the technological antecedents of the invention, all of which can be accessed in computerized form. Among this information are "references" or "citations". It is the patent examiner who determines which citations a patent must include. The citations serve the legal function of delimiting the scope of the property right conveyed by the patent. The granting of the patent is a legal statement that the idea embodied in the patent represents a novel and useful contribution over and above the previous state of knowledge, as represented by the citations. Thus, in principle, a citation of patent X by patent Y means that X represents a piece of previously existing knowledge upon which Y builds (Jaffe, 1993). Chapter 3 of the thesis digs deeper into this, identifying technological trajectories in the mining sector at the global level, using patent citation networks.

The prior art of the invention (patent) cited in patent documents provides useful information about the diffusion of technologies. Jaffe and Rassenfosse (2017) stress that the citations received by a patent from subsequent patents (forward citations) inform us about the technological descendants of the patented invention. A patent that is never cited was a technological dead end. A patent with many or technologically diverse forward citations correspond to an invention that was followed by many or technologically diverse descendants. The number of citations a patent application receives in subsequent patent applications (forward citations) has been found to be strongly associated with the economic value of patents (Harhoff, Narin, Scherer and Vopel, 1999) and the social value of inventions (Trajtenberg, 1990). The number of forward citations is one of the most frequently used value indicators and can be an important proxy for the quality of an innovation (OECD, 2009).

Table 1 reports information on the patent family size for Latin American mining patents. This is also compared to the countries that are on the global technological frontier in mining. Precisely, in the second column of Table 1, we report the maximum patent family size in Latin America and the countries on the global frontier. Furthermore, the third column of Table 1 reports the percentage of mining patents,

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[32] A patent is a property right in the commercial use of a device. For a patent to be granted, the invention must be nontrivial, meaning that it would not appear obvious to a skilled practitioner of the relevant technology, and it must be useful, meaning that it has potential commercial value.

invented in Latin America and in other countries, grouped in families with a size of less than 5 patents (i.e. a very small size)[33].

The results indicate that Latin America has one of the smallest sizes of patent families in comparison to the countries on the global technological frontier in mining[34]. The table further indicates that Latin America has a relatively large share of mining patents that are in families of less than five patents. Only the Russian Federation, the Republic of Korea and China perform worse than Latin America in terms of the indicator concerning family size, with the Russian Federation and the Republic of Korea having a smaller maximum family size than Latin America and China having very few patents in family sizes greater than 5. These results provide some initial evidence suggesting that the average quality of Latin American patents may not be that high, albeit relative to the leading countries.

Table 1 – Patent family size regarding the mining patents originating in Latin America and the countries on the global mining technological frontier, 1970-2015

Country of residence of the applicant (origin)	Max family size per each country in mining technologies, 1970-2015	Percentage of mining patents grouped in families with Size < 5
Russian Federation	20	96.7
The Republic of Korea	34	86.6
Latin America	50	53.1
Germany	80	49.9
Australia	107	37.8
China	111	98.9
France	120	32.3
Great Britain	191	35.8
Canada	200	45.9
Japan	212	80.9
United States	493	58.5

Source: Own elaboration based on WIPO Mining Database.

Turning to forward citations, Table 2 reports information on the share of total forward citations received by overall mining patents worldwide[35] (second column) and the average number of citations per mining patent (third column) for the frontier set of countries[36], for Latin America as a whole, and for the rest of the world. The results indicate that China, Japan and the US receive the highest share of forward citations worldwide in regards to their mining patents. Latin American mining patents only account for 0.36% of

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[33] The higher the share of mining patents in a region or a country with family size smaller than 5, the lower the quality of those patents.

[34] In this context, we compare a region (i.e. Latin America) with individual countries on the frontier. It is important to point out that our results are not subject to any kind of geographical aggregation bias because we examine patent quality, which is independent of the quantity of patents a country or a region owns.

[35] Defined as the ratio of forward citations received by the mining patents originating from the applicant country over total forward citations received by overall mining patents at the global level from 1970 to 2015.

[36] The same set of countries that lay on the global mining technological frontier used as a benchmark in the previous sections.

total forward citations worldwide between 1970 and 2015. They receive the lowest share of forward citations according to the second column of Table 2. The average number of citations of each mining patent is also one of the lowest, in comparison to both the countries on the global technological frontier in mining and the global trend more generally.

In Table 3, I focus on individual Latin America countries. Examining the second column of Table 3, the countries whose total mining patents received the highest share of forward citations within the Latin American region are Brazil (32.9%), Mexico (23.8%), Panama (14.9%), Chile (12.3%) and Venezuela (9.5%), with the Latin American countries with the highest average number of forward citations per mining patent being Bolivia, Dominican Republic, Panama and Venezuela. Nevertheless, the positive results concerning Bolivia and the Dominican Republic are biased by the fact that there is a very small number of mining patents (i.e. a handful of patents) invented locally from 1970 to 2015. Thus, comparing the third column of Tables 2 and 3, it turns out that only Panama and Venezuela have an average share of forward citations for each mining patent higher than the global average (0.25). Summarising, the results in this section suggest that the quality of innovation being undertaken in Latin America lags behind that in the frontier countries.

Table 2 – Indicator of forward citations of mining patents in terms of origin*, 1970-2015

ORIGIN	% TOTAL FORWARD CITATIONS	AVERAGE NUMBER OF CITATIONS PER EACH PATENT
Australia	0.92	0.24
Canada	2.22	0.31
China	29.88	0.31
Germany	5.34	0.28
France	2.37	0.23
Great Britain	2.34	0.28
Japan	19.29	0.37
The Republic of Korea	1.70	0.25
Russian Federation	2.11	0.06
United States	23.18	0.21
Latin America	**0.36**	**0.15**
Rest of the world	10.65	0.25
World (total)	100.00	0.25

*origin = country of origin of the applicant.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT dataset.

Table 3 – Indicator of forward citations of mining patents in terms of origin* in individual Latin American countries, 1970-2015

ORIGIN	% TOTAL FORWARD CITATIONS within LATAM	AVERAGE NUMBER OF CITATIONS PER EACH PATENT
Argentina	4.85	0.15
Bolivia	0.05	0.40
Brazil	32.93	0.10
Chile	12.26	0.14
Colombia	0.30	0.05
Cuba	1.17	0.09
Dominican Republic	0.05	0.33
Ecuador	0.02	0.01
Mexico	23.77	0.19
Panama	14.94	0.42
Peru	0.09	0.01
Uruguay	0.09	0.21
Venezuela	9.48	0.28
Total Latin America	100.00	

*origin = country of origin of the applicant.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT dataset.

2.4 Discussion

The results presented above indicate the Latin America has a strong specialization in the extraction and export of mining products, with inward FDI being a major activity that is both driving and being driven by this specialization pattern. At the same time, the results further show that Latin America has not been able to develop a specialization in other activities within the mining sector, notably mining equipment production and mining innovation, with the innovation taking place in the mining sector being of a low quality in comparison to frontier countries. In this section, I discuss some of the potential reasons for these results, focussing on the role of mining suppliers.

According to the Pavitt taxonomy (Pavitt, 1984), the mining sector is considered to share many characteristics of supplier-dominated innovation. This type of innovation is found in firms from predominantly traditional manufacturing industries such as textiles as well as agriculture, for example. Supplier dominated innovation firms rely on sources of innovation external to the firm, such as suppliers. Users of their products are price sensitive and the goal of innovation is cost cutting. Furthermore, the knowledge used in this type of firm has a low level of appropriability (Calzada Olvera and Iizuka, 2020).

Besides technological learning processes, knowledge-intensive suppliers have been key for turning natural resource industries into knowledge-based industries with high innovation capabilities. Knowledge-intensive suppliers, from equipment to engineering services, have also been fundamental for the competitiveness of the industry itself, and the emergence of knowledge intensive clusters (Urzua, 2013).

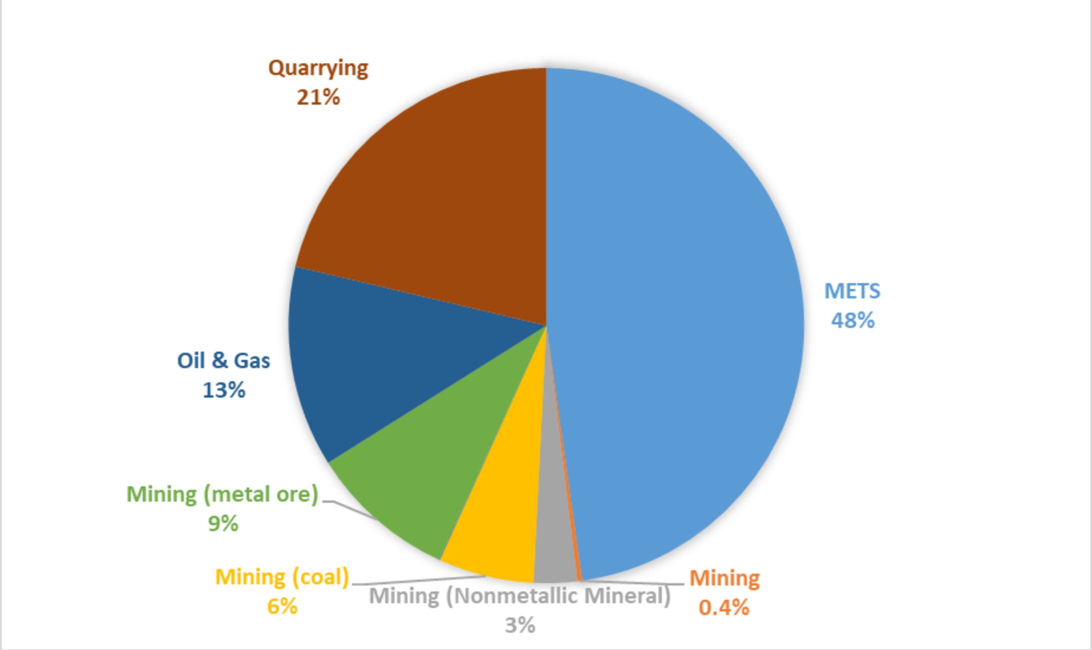
The relevance of suppliers of mining firms, i.e. METS[37] firms in mining innovation at the global level has been confirmed by several studies (Bartos, 2007; Calzada Olvera, 2021; Daly, Valacchi and Raffo, 2019; Francis, 2015; Iizuka, Pietrobelli and Vargas, 2019; Scott-Kemmis, 2013; Urzua, 2003).

The results described above suggest that this has not happened in the case of Latin America, with Latin America showing a declining comparative disadvantage in exporting (producing) mining equipment. Given such results, I examine whether and to what extent local METS carry out innovative activities in Latin America in comparison to the global trend.

In the mining sector, firms account for around three quarters of the applications that carry out patenting activities both at the global level and in Latin America (see Appendix C on this). Investigating the type of firms that undertake inventive activity in mining technologies, Figure 12 describes the particular types of firms (using information on their economic sector from the ORBIS dataset) that undertake mining-related patenting activities, both for the world as a whole and for Latin America.

Figure 12 – Share of mining patents divided in terms of firm economic sector, 1970-2015 (average)

a) World



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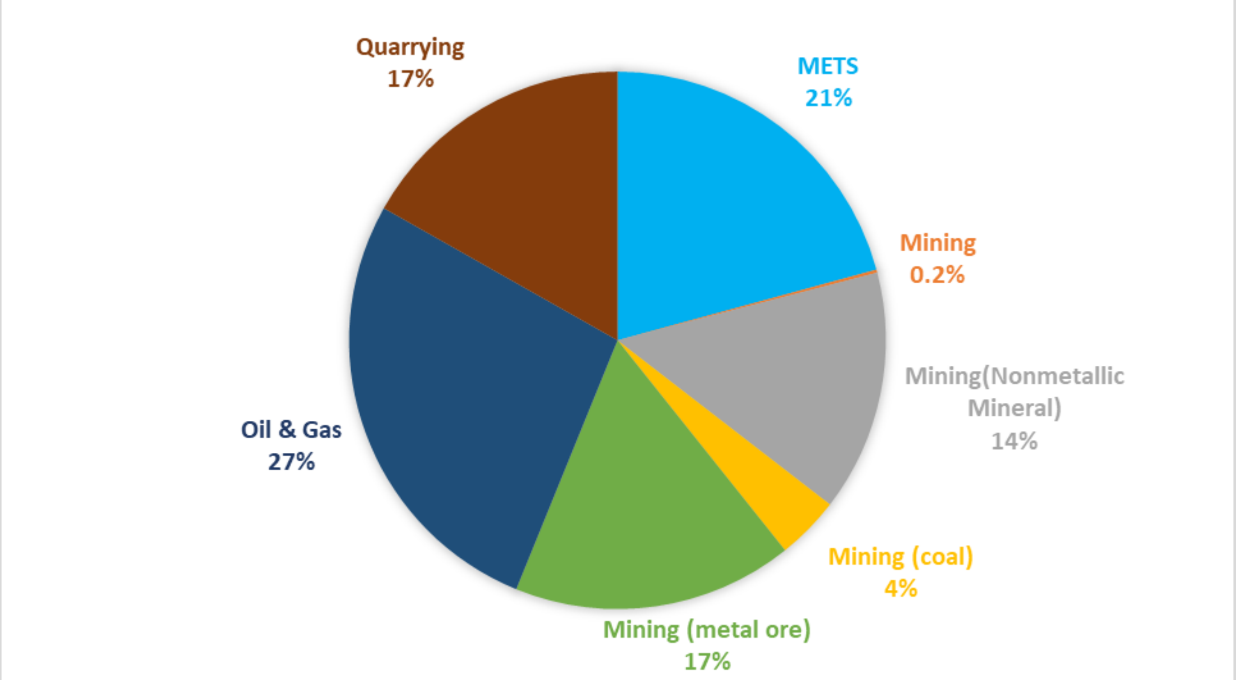
[37] Scott-Kemmis (2013) states that the METS include, among others: core engineering design & project management (EPCM), general support services, information technology equipment & related services, consulting services, specialized technology, core mining & processing equipment, general equipment and components and other services.

b) Latin America



Source: Own elaboration based on WIPO Mining Database and BVD ORBIS.

Figure 12a indicates that around half of patent applications in the mining sector globally are taken out by METS firms (48%), followed by quarrying firms (21%), mining firms (18%) and oil and gas companies (13%). This confirms the fact that innovation in the mining industry is supplier-dominated. In Latin America, there is a higher percentage of firms that innovate in mining technologies that belong to the oil & gas (27%) and the mining sector (35%), in comparison to the global average (13% and 18.4% respectively). Nevertheless, the most relevant difference between Figures 12a and 12b is that Latin America has, on average, a much lower share of mining patents applied for by METS firms (21%) in comparison to the global share. Such a difference may be a key explanation for why Latin America performs relatively poorly in mining innovation. This result on the relative lack of involvement of METS in patent applications in Latin American countries is further confirmed when comparing individual Latin American countries to countries on the global mining frontier[38] (see Appendix D).

Results depicted in Figure 12 are averages over the period 1970-2015. To examine whether the outcomes depicted in Figure 12 show variation over time, Figure 13 reports information on the share of different types of firm in mining innovation (i.e. patent applications) by year, again for both the world as a whole and for Latin America.

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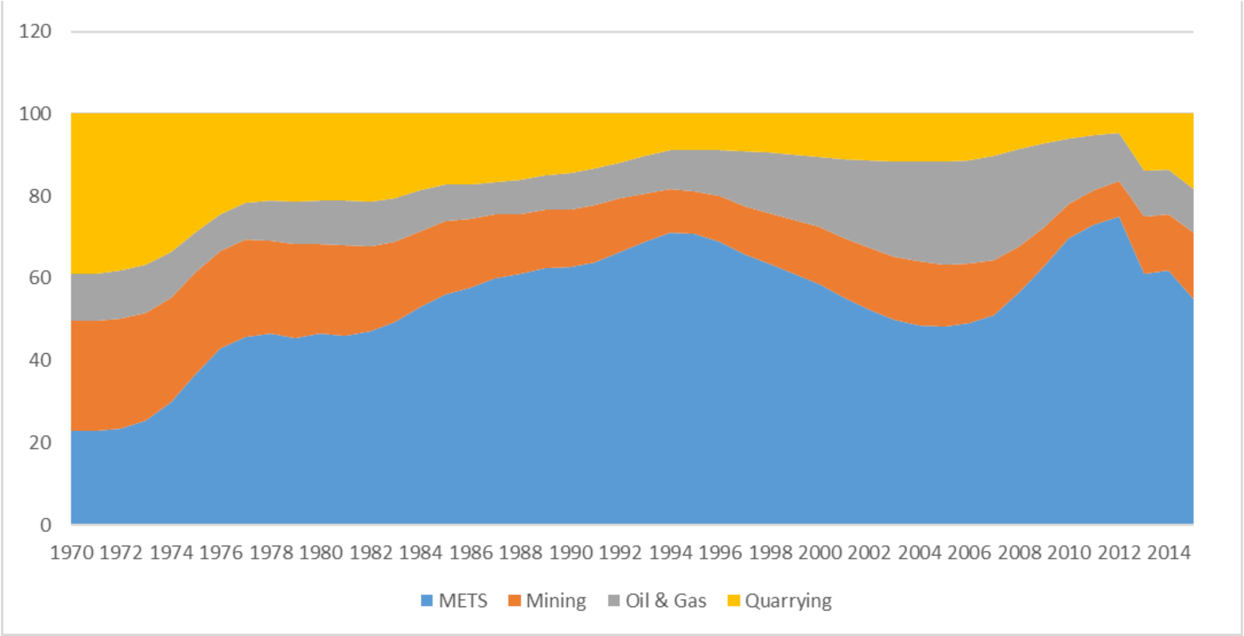
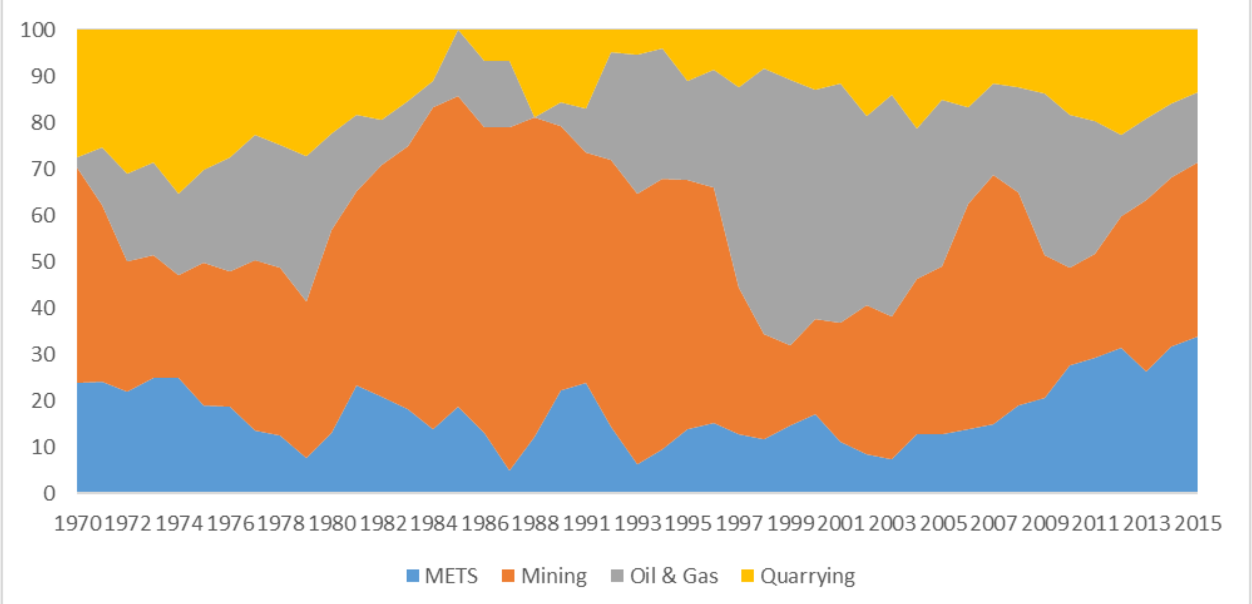
[38] One of the reasons why the countries on the global mining technological frontier are better at mining innovation than Latin American countries may relate to the fact that their innovation systems host innovative stakeholders from different industries that are likely to develop mining innovation. Hence, stronger linkages between mining companies and third parties are created (Bartos, 2007).

Figure 13 - Share of mining patents divided in terms of firm economic sector over time, 1970-2015

a) World



b) Latin America



Source: Own elaboration based on WIPO Mining Database and BVD ORBIS.

Figure 13a indicates that the share of METS in patent applications increased over time from just over 20% in 1970, accounting for more than half of all applications from the 1980s onwards. Most recently, the share of METS has decreased, though it still remains above 50%. In contrast, the results in Figure 13b show that mining firms have played a dominant role in Latin America in mining patenting activity for much of the period considered, and especially from the beginning of the 1980s to the end of the 1990s. Mining firms' patenting activity diminished, mainly in favour of oil & gas companies, between the end of the 1990s and the first half of 2000s. METS companies have played a generally minor role in patenting activity in Latin America, accounting for less than 25% of all patent applications for much of the period. Since the early 2000s however, the share of METS has increased significantly from below 10% in 2003 to above 30% in 2015. The extent to which this increase is broad-based, however, remains a concern with Calzada Olvera (2021; p. 2) arguing that while in recent years some suppliers in Latin America have made important contributions to increasing innovation in the mining industry, most suppliers have not been able to do so.

In considering the reasons for the lack of broad-based innovative activity by METS firms in Latin America, several barriers to local suppliers' innovative performance in Latin America have been identified. Calzada Olvera (2021), for example, highlights a number of barriers including a lack of testing spaces for prototypes to broader issues, conservative business attitudes, hierarchical governance of the value chain and limited communication channels between mining companies and suppliers. A further major barrier often faced by suppliers is the risk-aversion to work with local suppliers. When there are high transaction costs, complexity of information and asset specificity, mining companies prefer long-standing suppliers, which in only few instances are local. As Stubrin (2017) points out, mining firms' operators are loyal to international suppliers, they trust their technologies and they have been trained in using them[39]. Thus, such preferences reinforce the technological lock-in. Moreover, since interactions between suppliers and mining firms are more of a transactional nature rather than collaborative, with a hierarchical governance of the value chain often prevailing (Pietrobelli, Marin and Olivari, 2018), innovation risks end up being absorbed almost entirely by the supply firm (Figuereido and Piana, 2017).

2.5 Conclusion

In this chapter, I have shown that Latin America has developed a strong specialization in the extraction and export of mining products. However, we have highlighted a remarkable heterogeneity in specialisation patterns both across countries and across sub-sectors of the mining industry. Using data on exports as well as inward FDIs, I find that Latin America has not been able to develop specialization in higher value-added activities within the mining value chain, such as the production and export of mining equipment and the production of mining technology, especially in those key technologies that are driving mining technology. Indeed, Latin America has seen a declining specialization in mining innovation in recent years. Moreover, the innovation that is taking place in Latin America is not of a high quality. The results thus suggest that Latin America relies on foreign technology and equipment for the mining sector (i.e., it is a technology user) rather than being a developer of new technology and equipment. This pattern appears to be reinforced in recent years, with an increasing specialization in mining production, but a decreasing specialization in mining equipment production and mining innovation. This reveals the presence of diverging specialization patterns over time, i.e. the specializations in mining production (of mineral commodities) and in mining innovation/technology are moving away from each other in recent years. In Appendix E, we provide a short case study on Peru that, based on the results of this chapter, is the Latin American country where the mismatch between production specialisation and innovation specialisation in the mining sector turns to be the greatest.

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[39] This is in line with the findings in Section 3.2, referring to the specialization of Latin America in importing (using) mining equipment from foreign equipment manufacturers, i.e. suppliers.

Production specialisation without innovation specialisation may lead to a lack of long-run development (Dosi and Tranchero, 2021). In fact, Cimoli et al. (2011) argue that a country having comparative advantage in exporting natural resources commodities (e.g. mining), only relying on the static rents provided by natural resources, will certainly have troubles in achieving natural resource-based development if it does not manage to use these exports as a basis for learning, linkage effects, technological learning. In other words, more important than having or not having natural resources production specialisation is to effectively use natural resources as a basis for learning, innovation and structural upgrading.

One potential explanation for the poor innovative performance of Latin America in mining is that local METS firms, which are supposed to be key innovators for the mining industry, are much less active in mining innovation than at the global level. While at the global level, 48% of global mining patents are invented by METS companies, in the case of Latin America just 21% of mining patents are invented by METS. Such a conclusion is reinforced by the fact that Latin America is not specialized in exporting mining equipment, suggesting weaknesses of local equipment suppliers. Conversely, Latin America is specialized in importing foreign technology embodied in mining equipment, relying on foreign suppliers. Relatedly, Dosi, Riccio and Virgillito (2021) found that countries stuck into supplier-dominated sectors seem to have missed major opportunities of catching-up. Support for technological upgrading will be required to allow local suppliers of goods and services to the mining industry enhance their technological capacities. Optimal policy requires that industrial and technology policy are accordingly aligned and complementary (Kaplan 2012). In fact, natural resource-based economic development is not the result of the mere extraction of mineral commodities itself but rather of the development of productive linkages (Kaplinsky, 2011), especially with medium and high knowledge intensity sectors (Calzada Olvera and Foster-McGregor, 2018).

It is often considered that the accumulation of technological capabilities is an important tool to avoid the resource curse and to involve more local mining suppliers in mining activities (Cimoli and Porcile, 2011). The fact that Latin America appears to have not been able to upgrade in the mining sector suggests a structural weakness that may place limitations on the growth of the mining sector, and on the role that the mining sector can play as a development escalator. The widening of the technology gap in the Latin American region in the last decades may well reflect a state of hysteresis, which may require a thorough redefinition of industrial and technology policies to overcome.

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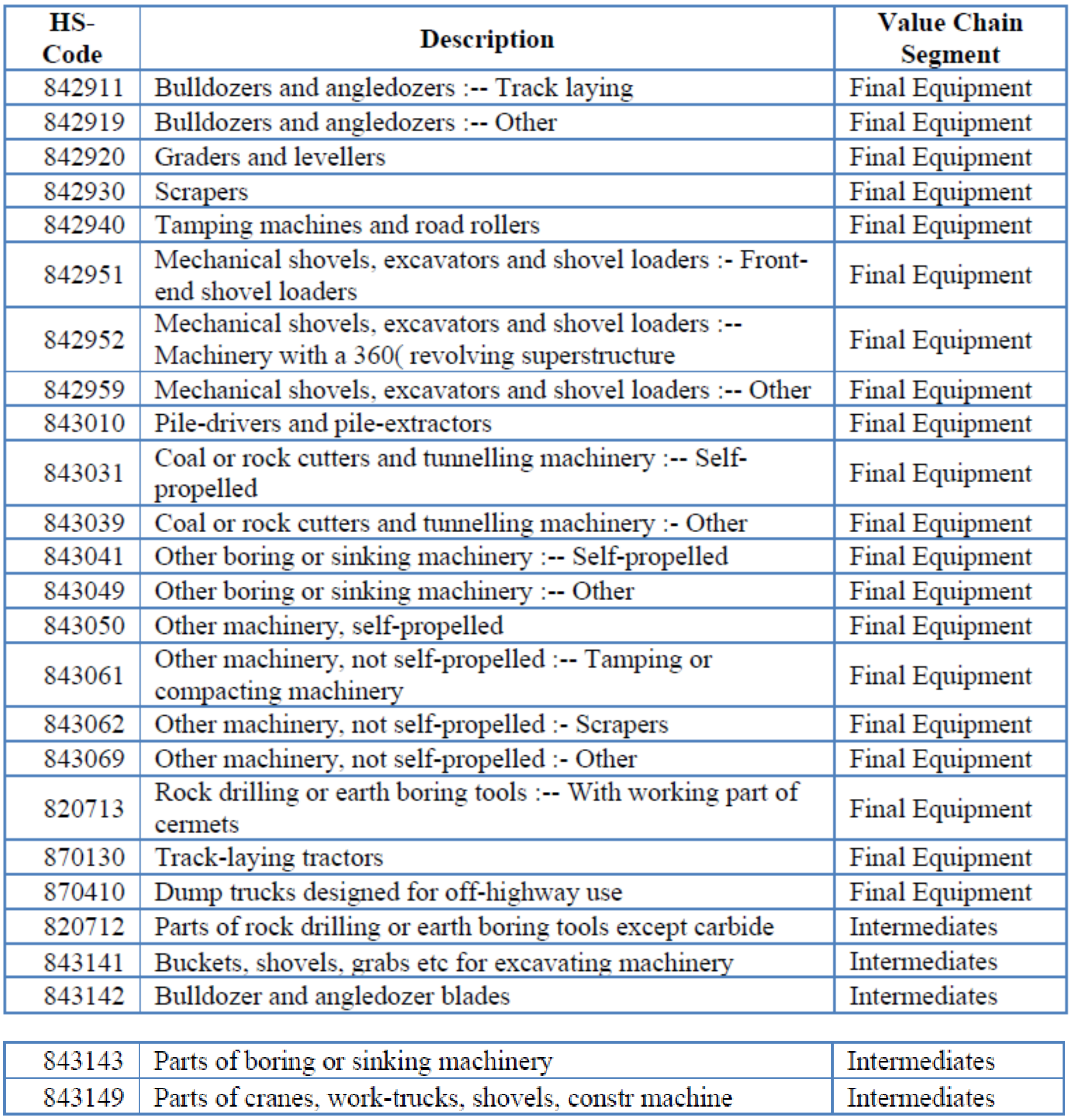
Appendix A Product categories related to mining equipment

Table A1 – Surface and underground mining equipment



HS-Code	Description	Value Chain Segment
842911	Bulldozers and angledozers :-- Track laying	Final Equipment
842919	Bulldozers and angledozers :-- Other	Final Equipment
842920	Graders and levellers	Final Equipment
842930	Scrapers	Final Equipment
842940	Tamping machines and road rollers	Final Equipment
842951	Mechanical shovels, excavators and shovel loaders :- Front-end shovel loaders	Final Equipment
842952	Mechanical shovels, excavators and shovel loaders :-- Machinery with a 360(revolving superstructure	Final Equipment
842959	Mechanical shovels, excavators and shovel loaders :-- Other	Final Equipment
843010	Pile-drivers and pile-extractors	Final Equipment
843031	Coal or rock cutters and tunnelling machinery :-- Self-propelled	Final Equipment
843039	Coal or rock cutters and tunnelling machinery :- Other	Final Equipment
843041	Other boring or sinking machinery :-- Self-propelled	Final Equipment
843049	Other boring or sinking machinery :-- Other	Final Equipment
843050	Other machinery, self-propelled	Final Equipment
843061	Other machinery, not self-propelled :-- Tamping or compacting machinery	Final Equipment
843062	Other machinery, not self-propelled :- Scrapers	Final Equipment
843069	Other machinery, not self-propelled :- Other	Final Equipment
820713	Rock drilling or earth boring tools :-- With working part of cermets	Final Equipment
870130	Track-laying tractors	Final Equipment
870410	Dump trucks designed for off-highway use	Final Equipment
820712	Parts of rock drilling or earth boring tools except carbide	Intermediates
843141	Buckets, shovels, grabs etc for excavating machinery	Intermediates
843142	Bulldozer and angledozer blades	Intermediates
843143	Parts of boring or sinking machinery	Intermediates
843149	Parts of cranes, work-trucks, shovels, constr machine	Intermediates

Source: Bamber, Fernandez-Stark and Gereffi (2016; pp. 52-54).

Table A2 – Mineral processing equipment

HS-Code	Description	Value Chain Segment
845510	Tube mills	Final Equipment
845521	Other rolling mills :-- Hot or combination hot and cold	Final Equipment
845522	Other rolling mills :-- Cold	Final Equipment
847410	Sorting, screening, separating or washing machines	Final Equipment
847420	Crushing or grinding machines	Final Equipment
847439	Mixing or kneading machines :-- Other	Final Equipment
847480	Machines to agglomerate, shape, mould minerals or fuel	Final Equipment
841370	Centrifugal pumps nes	Final Equipment
841710	Furnaces and ovens for the roasting, melting or other heat-treatment of ores, pyrites or of metals	Final Equipment
847982	Other machines and mechanical appliances :-- Mixing, kneading, crushing, grinding, screening, sifting, homogenising, emulsifying or stirring machines	Final Equipment
845530	Rolls for rolling mills	Intermediates
845590	Other parts for rolling mills	Intermediates
841790	Parts for Furnaces and ovens for the roasting, melting or other heat-treatment of ores, pyrites or of metals	Intermediates
847490	Parts	Intermediates
732591*	Balls, iron or steel, cast, for grinding mills	Intermediates

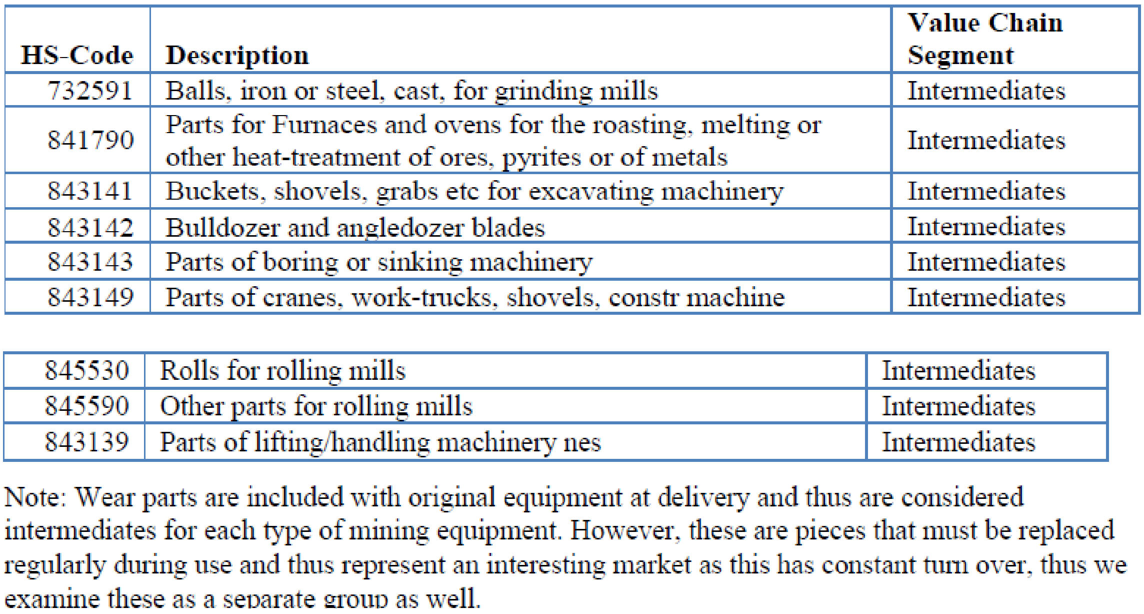
Source: Bamber, Fernandez-Stark and Gereffi (2016; pp. 52-54).

Table A3 – Materials handling equipment

HS-Code	Description	Value Chain Segment
842831	Mine conveyors/elevators, continuous action Other continuous-action elevators and conveyors, for goods or materials :-- Specially designed for underground use	Final Equipment
842850	Mine wagon pushers, locomotive or wagon traversers, wagon tippers and similar railway wagon handling equipment	Final Equipment
842890	Other lifting handling or loading machinery	Final Equipment
843131	Parts of lifts, skip hoist or escalators	Intermediates
843139	Parts of lifting/handling machinery nes	Intermediates
843110	Parts of hoists and winches	Intermediates

Source: Bamber, Fernandez-Stark and Gereffi (2016; pp. 52-54).

Table A4 – Wear parts



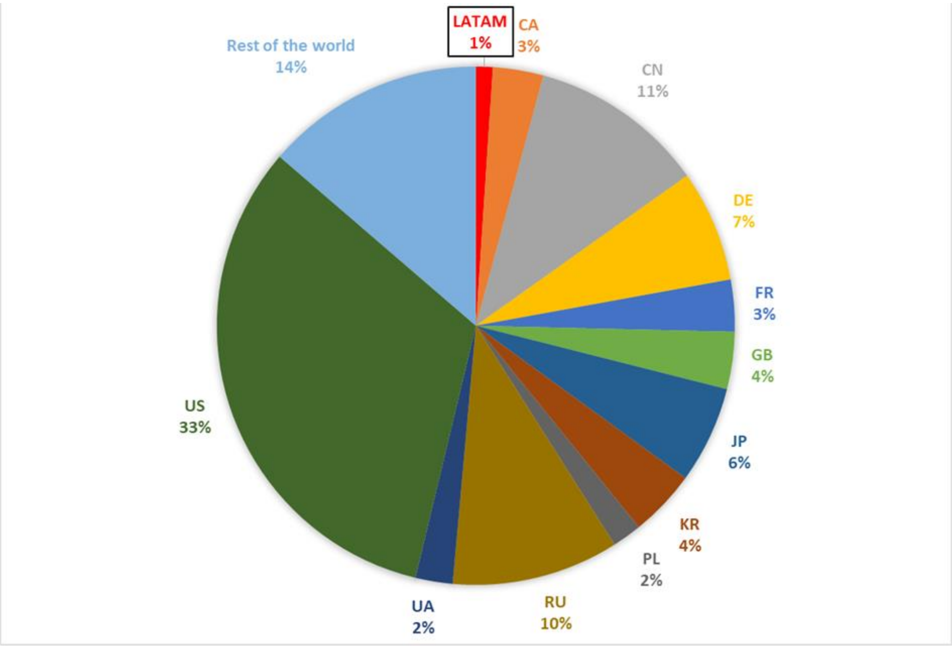
HS-Code	Description	Value Chain Segment
732591	Balls, iron or steel, cast, for grinding mills	Intermediates
841790	Parts for Furnaces and ovens for the roasting, melting or other heat-treatment of ores, pyrites or of metals	Intermediates
843141	Buckets, shovels, grabs etc for excavating machinery	Intermediates
843142	Bulldozer and angledozer blades	Intermediates
843143	Parts of boring or sinking machinery	Intermediates
843149	Parts of cranes, work-trucks, shovels, constr machine	Intermediates
845530	Rolls for rolling mills	Intermediates
845590	Other parts for rolling mills	Intermediates
843139	Parts of lifting/handling machinery nes	Intermediates

Note: Wear parts are included with original equipment at delivery and thus are considered intermediates for each type of mining equipment. However, these are pieces that must be replaced regularly during use and thus represent an interesting market as this has constant turn over, thus we examine these as a separate group as well.

Source: Bamber, Fernandez-Stark and Gereffi (2016; pp. 52-54).

Appendix B Share of mining patents in terms of inventor's country of residence worldwide

Figure B1 – Share of mining patents in terms of inventor's country of residence worldwide, 1970-2015



Note:

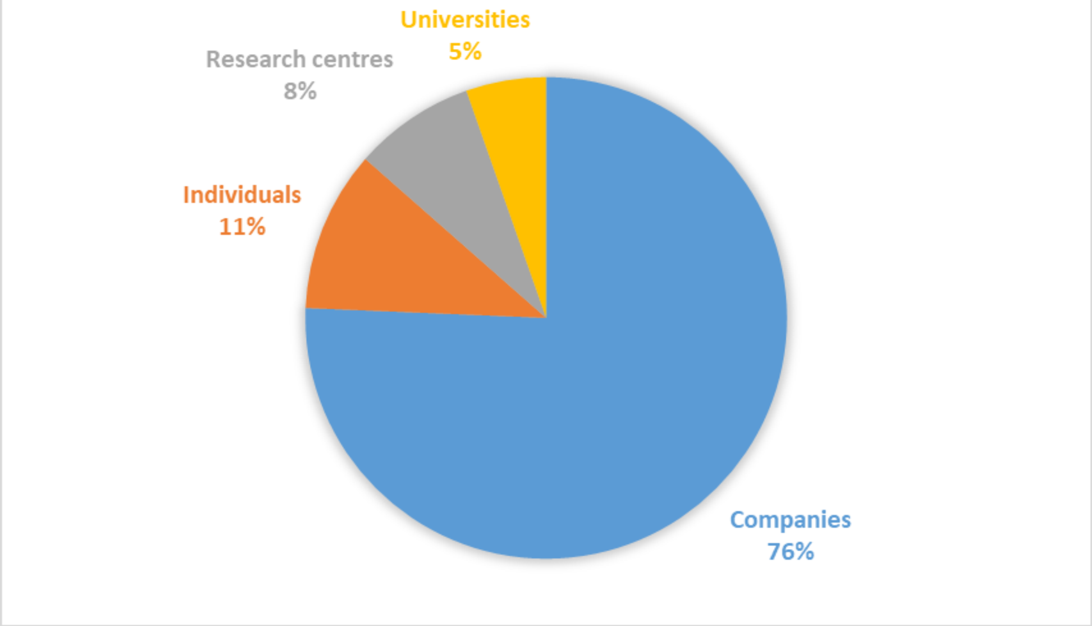
- LATAM does not include Haiti, Paraguay, Guadeloupe, Martinique (MQ), Saint Martin and Saint Barthèlemy because they have no mining patents in terms of applicant country.
- "Rest of the world" represents all the other countries, that are not labelled in the chart, with less than 1 percent each.
- We use counts of patent applications to make these statistics.

Source: own elaboration based on WIPO Mining Database.

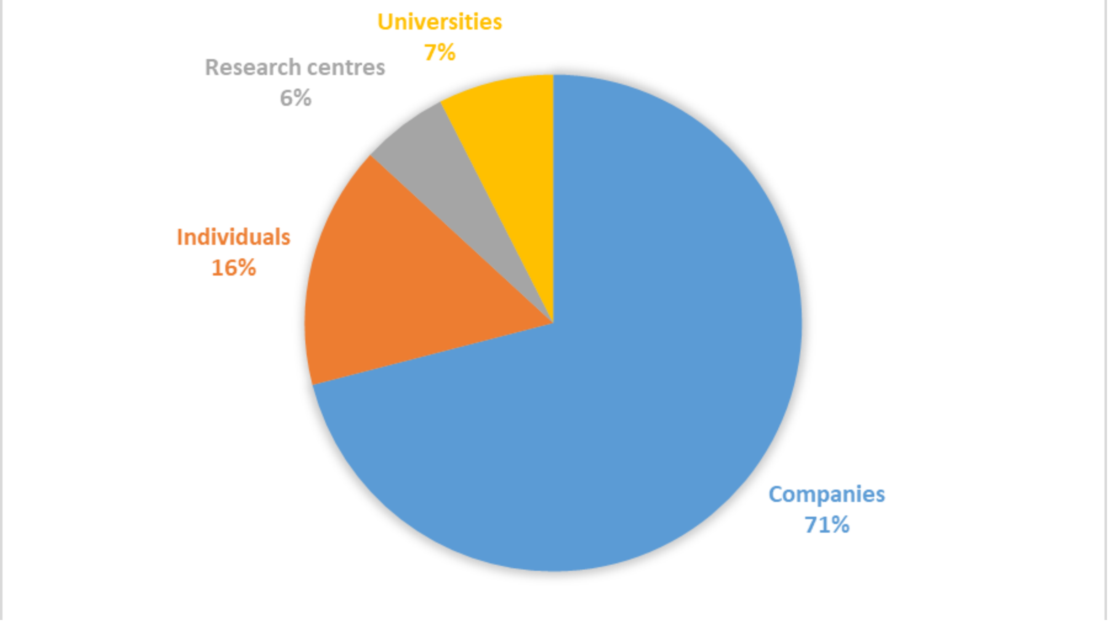
Appendix C Share of mining patents per type of applicant

Figure C1 – Share of mining patents per type of applicant, 1970-2015

1) World



2) Latin America

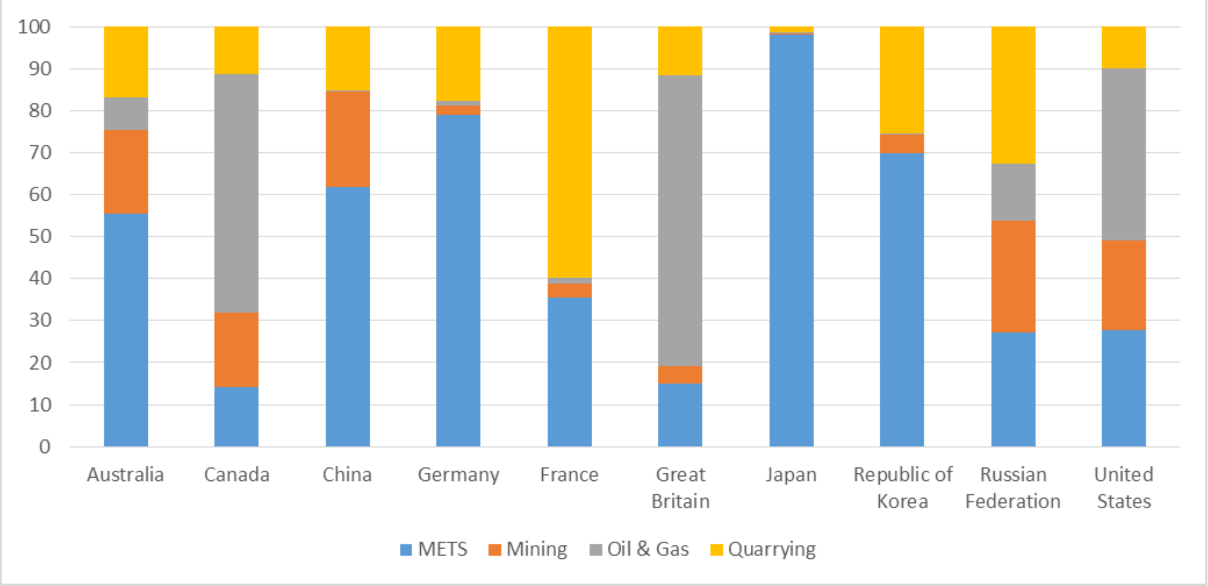


Source: Own elaboration based on WIPO Mining Database and BVD Orbis.

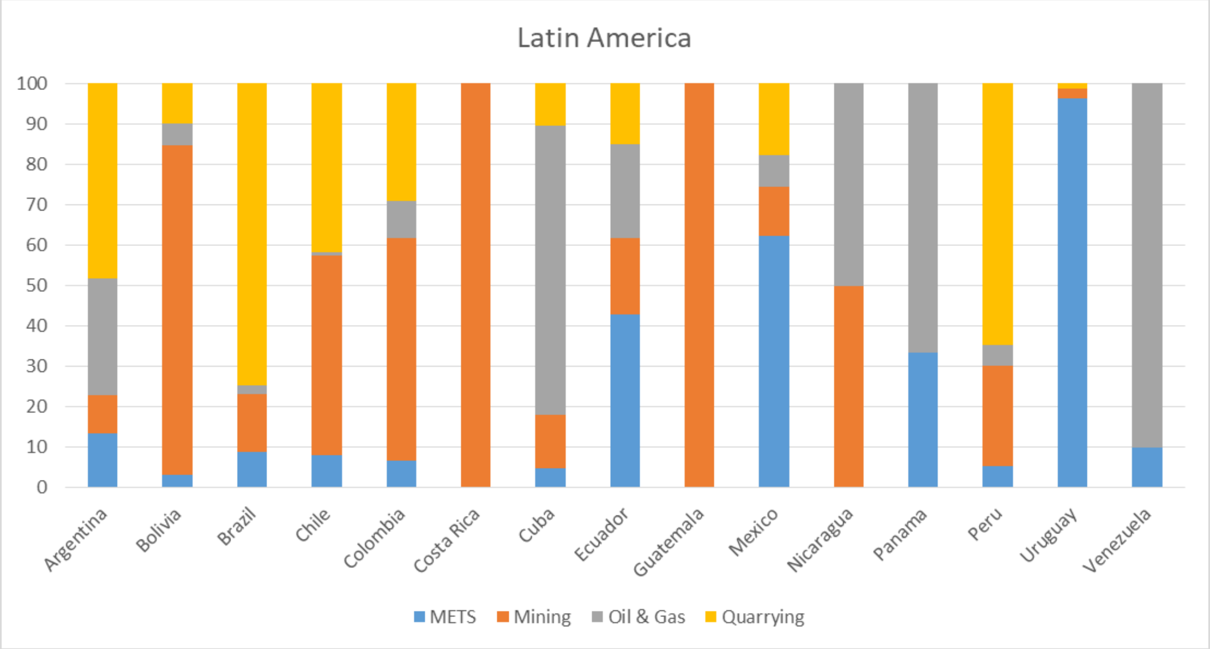
Appendix D Share of mining patents distributed in terms of applicant firm (economic sector) per each country

Figure D1 - Share of mining patents (origin*) distributed in terms of applicant firm (economic sector) per each country, 1970-2015

1) Countries on the global mining technological frontier



2) Latin America



*origin = country of origin of the applicant firm.

Source: Own elaboration based on WIPO Mining Database and BVD ORBIS.

Appendix E Case study on Peru

Structural weaknesses associated to specialisation in mining production: the case of Peru

We investigate the presence of some structural weaknesses associated to specialisation in natural resource production for a developing resource-abundant country, namely Peru. Following the rationale behind the general introduction of this thesis (i.e. Chapter 1), we examine whether there are negative factors that, associated with specialisation (dependence) in natural resources, might lead to resource curse. It is not our intention to examine whether Peru is resource cursed, which would require a greater statistical analysis. Hence, our aim is to ascertain whether it is more likely that Peru may run into resource curse and whether there are pitfalls regarding natural resource-based development in Peru, due its (over)specialization in the extractive sector.

Why Peru?

We chose to study Peru for the following reasons.

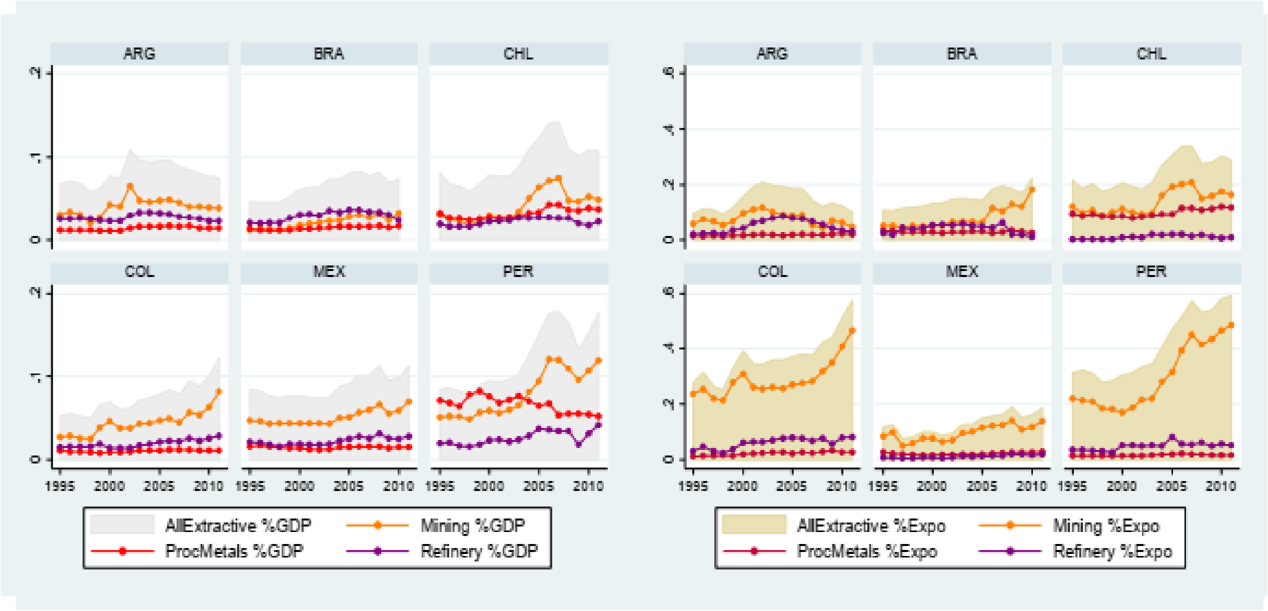
Based on the results of Chapter 2, we have found that Peru is over-specialised in producing mineral commodities. Precisely, Peru is over-specialised in exporting (Figure 1 of Chapter 2) and in attracting inward FDI (Figure 2 of Chapter 2) in the mining sector. Moreover, Peru is one of the most dependent

Latin American countries on mining. Conversely, the results in Chapter 2 also indicate that Peru has not been able to develop specialization in higher value-added activities within the mining value chain, such as the production and export of mining equipment (Figure 4 of Chapter 2) and the production of mining technology (Figure 8 of Chapter 2), especially in those key technologies that are driving mining technology (Figure 10 of Chapter 2). Indeed, Peru has seen a declining specialization in mining innovation in recent years. Moreover, the innovation that is taking place in Peru is of the lowest quality, among the Latin American countries in our sample (see Table 3 of Chapter 2 concerning the patent quality indicator based on forward citations). The results thus suggest that Peru relies on foreign technology and equipment (Figure 6 of Chapter 2) for the mining sector (i.e., it is a technology user) rather than being a developer of new technology and equipment, revealing weaknesses of local equipment suppliers. Furthermore, the specialisation in mining production (of mineral commodities) is moving away from specialisation in mining innovation/technology from 2004 to 2014, revealing diverging specialisation patterns (production vs innovation) during time. It is worth remembering that production specialisation without innovation specialisation may lead to a lack of long-run development (Dosi and Tranchero, 2018) as argued in Chapter 2 (and in Chapter 1, i.e. the general introduction). Based on our results, Peru is among the Latin American countries where this mismatch between production specialisation and innovation specialisation is more pronounced. Finally, Peru is the Latin American country with the lowest level innovativeness (after Bolivia) of local METS companies, i.e. suppliers to mining firms (see Figure D1 in appendix D).

Peru recently revived its long-established mining tradition and has become the world's biggest producer of silver; the second biggest producer of zinc and copper; the third of tin; the fourth of lead and molybdenum; and the fifth of gold (Ministerio de Energìa y Minas-Perù, 2009).

A closer look at Latin America more generally shows that the mining sector has grown substantially in terms of its economic contribution (i.e. share of GDP and exports) with Peru being the most dependent on mining among the countries in Figure E1.

Figure E1 – Extractive sectors contribution to GDP and exports in Latin America, 1995-2010



Source: Calzada Olvera and Foster-McGregor's (2018; p. 10) elaboration with OECD data.

As a share in GDP, the mining sector grew from 1% to 4% in Brazil, 3% to 8% in Colombia, 5% to 12% in Peru, 5% to 7% in Mexico, 3% to 5% in Chile and 3% to 4% in Argentina. Calzada Olvera and Foster-McGregor (2018; p. 10) state that the share of mining in total exports in Mexico went from 8% to 14%, in Colombia from 24% to 46%, in Peru from 22% to 49%, in Brazil from 5% to 20%, and in Chile from 12% to 16%. Only Argentina had a decline from 6% to 5%.

In the case of the Peruvian mining sector, large foreign multinational companies govern the value chain (Molina, Olivari and Pietrobelli, 2016). 79% of total copper production can be accounted to four large firms (Antamina, Southern Peru Copper Cooperation, Cerro Verde and Antapaccay). Although the production of gold and silver is shared among more companies, a small number still comprises more than 50% of the total production. Six large firms produce 56% of Peruvian gold (Yanacocha, Barrick Misquichilca, Madre de Dios, Consorcio Minero Horizonte, Buenaventura and La Arena) and six large firms account for 54% of Peruvian silver (Buenaventura, Antamina, Ares, Volcan, Shungar and Milpo) (MEM, 2014).

Typically, large mining operations tend to be controlled by foreign MNCs, which perform little local innovation, govern hierarchically their value chains, set the rules of the game unilaterally and rely mostly on foreign suppliers for key, knowledge intensive, sensitive solutions (UNECA, 2013; Pietrobelli, Marin and Olivari, 2018). This is an impediment for diversification, local innovation and the involvement of local suppliers in the more promising stages of the value chain (Pietrobelli, Marin and Olivari, 2018). Venables (2016) confirms these views but, like most of the literature, looking mainly at traditional macroeconomic arguments, such as the impact on the balance of payments, "Dutch Disease" and rent seeking, and neglecting the potential offered by linkages and spillovers.

In this context, we examine the presence of some structural weaknesses associated to specialisation in the extractive industries (already described separately in the general introduction of this thesis) for Peru, using inward FDI data from fDi Markets Database[♣] from 2003 to 2014. In particular: the concentration of inward FDI in the extractive sector (a proxy for natural resource dependence) that is associated to the lack of diversification of productive activities, lack of innovation in the local extractive sector, weaknesses of institutions and local conflicts, pitfalls concerning local employment and environmental regulations.

[♣] fDi Markets Database is an online database provided by fDi Intelligence – a specialist division of Financial Times Ltd – which monitors cross-border investments covering all sectors and countries worldwide from 2003 onwards.
fDi Markets is an event-based (or deal-based) database, i.e. each entry is a project. Each project collects detailed information on announced cross-border greenfield investments (i.e. new wholly-owned subsidiaries, including joint ventures whether they lead to a new physical operation) from several publicly available information sources, including nearly 9000 media sources, over 1000 industry organizations and investment agencies, and data purchased from market research and publication companies.
fDi Markets reports an amount of information related to the type and geographical dimension of the investment. The database also provides details related to the type of the investment, such as the cluster, industry and subsector the investment is directed to, presenting also information on the main business activity involved in the project and a brief description of each individual FDI. The classification of business activities the investment project is related to is a key distinctive characteristic of the database and constitutes a crucial element for analysing the linkage between FDI patterns and GVCs. Business activities monitored by fDi Markets include both upstream stages, such as Research and Development (R&D), Design, Development and testing (DDT), and more downstream ones such as Manufacturing, Retail and Logistics.
We have access to the data recorded from 2003 to 2014. (Zanfei, Coveri and Pianta, 2019).
Further information on fDi Markets is available at https://www.fDimarkets.com/.

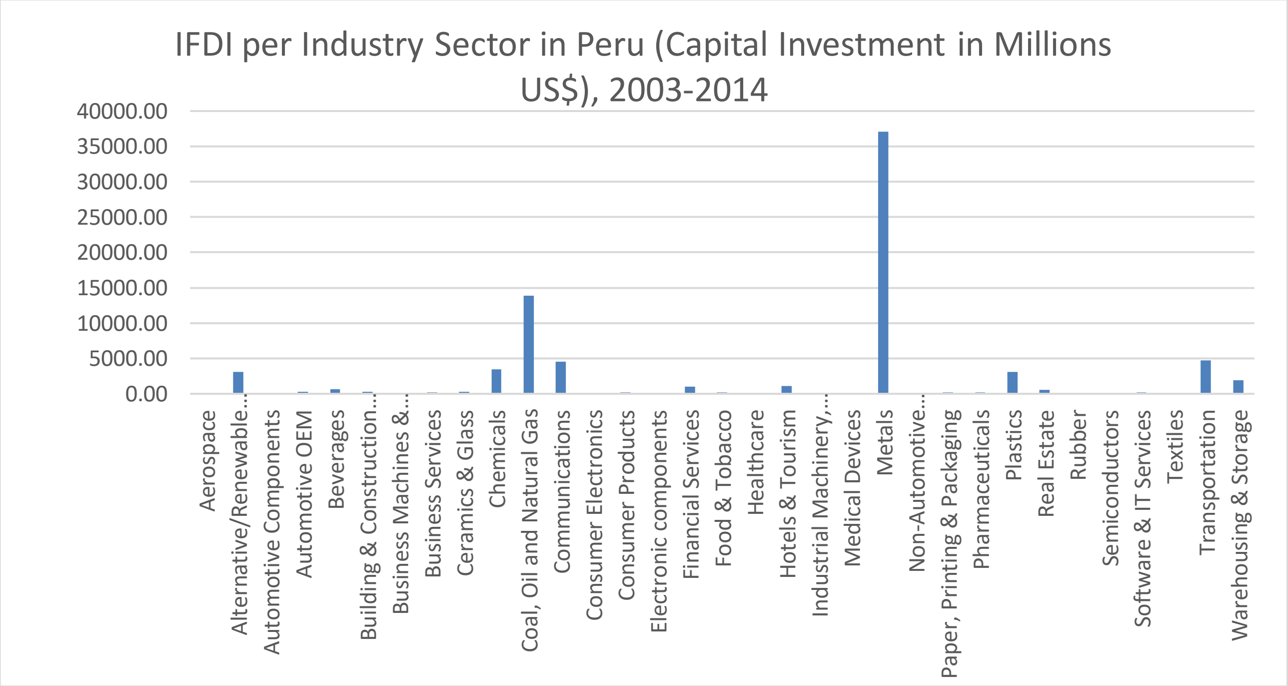
Concentration of inward FDI in the extractive sector (lack of diversification of productive activities)

Large mining operations tend to be controlled by foreign MNCs in Peru, which perform little local innovation, govern hierarchically their value chains, set the rules of the game unilaterally. This is an impediment for diversification, local innovation and the involvement of local suppliers in the more promising stages of the value chain (Molina, Olivari and Pietrobelli, 2016; Pietrobelli, Marin and Olivari, 2018).

Considering the strong presence of foreign MNCs in the Peruvian extractive sector (Molina, Olivari and Pietrobelli, 2016), we examine to what extent inward FDI projects are distributed among sectors in Peru, investigating whether productive activities are diversified. Hence, we examine whether the structural weakness related to the concentration of inward FDI in (dependence on) the extractive industry is present in this Latin American country.

Figure E2 portrays the distribution of inward FDI greenfield projects in Peru for the period 2003-2014, using fDi Markets Database.

Figure E2 – Inward FDI greenfield projects in terms of capital investment (Millions US$) in Peru, 2003-2014 (average)



Source: Own elaboration based on FDI Markets database.

Figure E2 represents that inward FDIs are heavily concentrated in the extractive sector in Peru, namely in the industry sectors “Coal, Oil and Natural Gas” and “Metals”. In particular, inward FDIs in the extractive sector (Coal, Oil and Natural Gas + Metals) represent 65.7% of total inward FDIs in all sectors in Peru from 2003 to 2014. If we focus only on inward FDI in the mining sector, the share is of 47.8%.

This reveals in a preliminary way that inward FDI in Peru are mainly concentrated in the extractive industries and it is a weakness of the Peruvian productive structure.

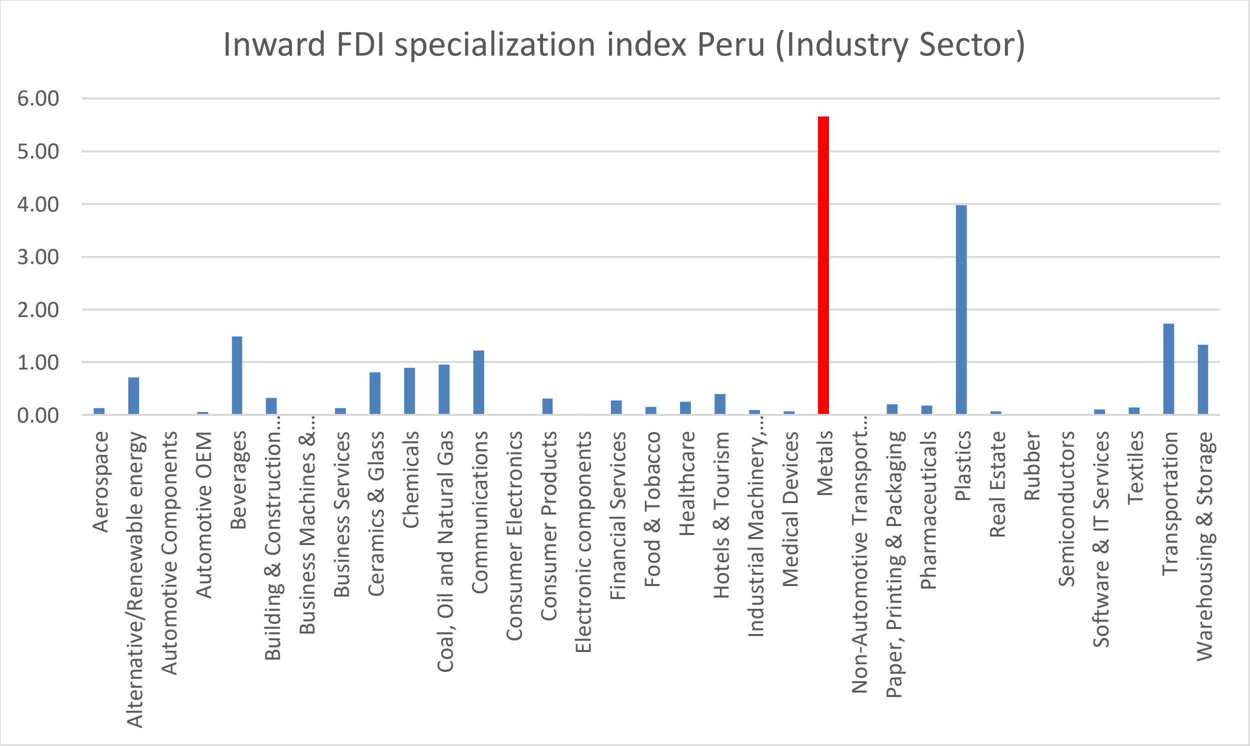
To confirm this pattern, we compute an inward FDI-based specialization index, i.e. Revealed Comparative Advantage (RCA) for each industry sector of the Peruvian economy, following Zanfei, Coveri and Pianta (2019).

The RCA based on inward FDI in industry *i* for the economy *k* is computed as follows:

$$\mathrm{RCA\_IFDI}_k^{i} = \frac{\dfrac{FDI^{i}_{k}}{\sum k \; FDI^{i}_{k}}}{\dfrac{\sum i \; FDI^{i}_{k}}{\sum k \sum i \; FDI^{i}_{k}}}$$

The specialization index for a given economy is by construction greater than one when the economy shows a relative specialization in (drawing FDIs in) that industry, i.e. when the share of FDIs received by the economy in that industry overcomes the average weight of the economy in the world in terms of FDIs in all industries. The inward FDI-based specialization index mirrors the Balassa index (Balassa (1965) – aimed at detecting revealed comparative advantages in international trade -, the main difference being that the latter is based on exports instead of inward FDIs. Figure E3 depicts the results.

Figure E3 – Inward FDI-based specialization index computed for each industry sector in terms of capital investment (Millions US$) regarding Peru, 2003-2014 (average)



Note: the over-specialisation in "Plastics" is due to a huge quantity of inward FDIs in year 2007.

Source: own elaboration based on fDi Markets database.

Figure E3 shows that Peru is over-specialized in the mining sector (industry sector "Metals") with an inward FDI-based specialization index equal to 5.65, and it is specialized in very few other industry sectors, i.e. plastics (the most significant after "Metals"), transportation, beverages, communications and warehousing & storage. The results confirm that Peru is heavily dependent on the extractive sector, i.e. inward FDIs in the Peruvian economy are mostly concentrated in the extractive sector, with the neglect of other promising industries such as manufacturing and services. This also reveals a lack of diversification of the productive structure.

This is not in line with the possible strategy to achieve natural resource-based development underpinned in this thesis, i.e. an economy should have a diffuse production specialization in several or many sectors of the economy (Hausmann, Hwang and Rodrik, 2007; Hidalgo and Hausmann, 2009; Bontadini and Savona, 2019). In addition, an economy should have a specialisation in innovation in the sector for which it has a production specialisation (Cimoli et al., 2011).

Lack of innovation in the Peruvian extractive sector

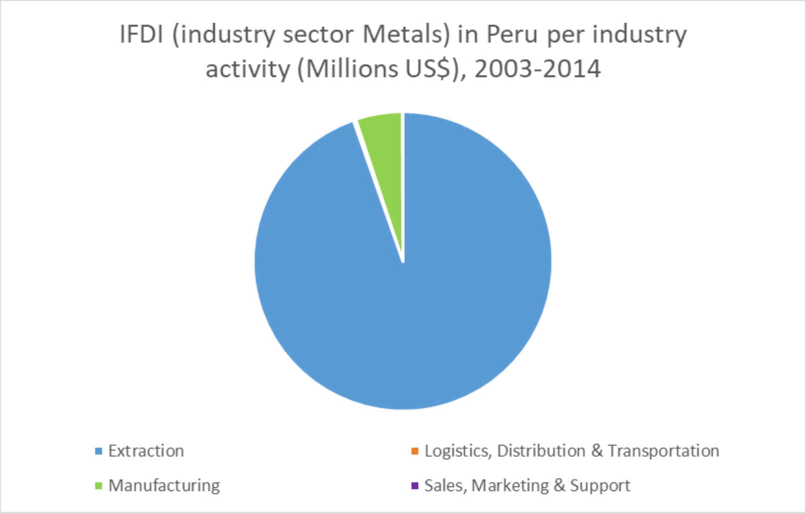
In Chapter 2 of this thesis, we have found that Peru, despite its strong specialisation in the production of mineral commodities, is de-specialised in exporting (producing) mining equipment (with trade data) and in producing mining-related knowledge (with patent data). To complete the picture, given the strong presence of extractive sector foreign multinationals in Peru, we examine whether Peru is able to produce innovation in the extractive sector using FDI data.

Specifically, we measure innovation activities taking into account whether inward FDIs concentrate in low (lack of innovation) or high (presence of innovation) value added activities along the GVC (Global Value Chain).

We choose FDI because it is seen by many as a prime means of a country engaging in GVCs (Foster-McGregor, Kaulich and Stehrer, 2015). GVCs are usually coordinated by MNCs, with cross-border trade of inputs and outputs taking place within their network of affiliates, contractual partners and arms-length suppliers (UNCTAD, 2013; Foster-McGregor, Kaulich and Stehrer (2015; p. 32)). Countries that have a higher presence of FDI (e.g. Peru) therefore are likely to have a higher level of participation in GVCs, and may help generate spillovers to other domestic firms as well as through spin-offs. In fact, Foster-McGregor, Kaulich and Stehrer (2015) argue that the participation in GVCs, the exposure to international markets and foreign competitors, the potential for technology transfer and spillover effects arises. Unfortunately, it does not always happen because the possibility of positive spillovers depends on several factors, e.g. the quality of inward FDI, the sectors where they concentrate and the specific local context.

Considering that inward FDI in the mining sector in Peru represent nearly half of total inward FDI from 2003 to 2014, Figure E4 reports in which GVC stages (business activities) inward FDIs in the Peruvian mining sector concentrate. The aim is to detect whether and to what extent innovation activities are carried out at the local level.

Figure E4 – Inward FDI projects in the mining sector in terms of capital investment (Millions US$) in Peru per business activity (Capital Investment in Millions of US$), 2003-2014 (average)



Source: own elaboration based on fDi Markets database.

Figure E4 depicts that foreign MNCs involved in the Peruvian mining sector entirely concentrate investments in low value added activities along the GVC, i.e. extraction and manufacturing. Inward FDIs in medium-high added value activities along the GVC such as design, development & testing, education

& training, headquarters, research & development are nearly not present. This identifies a lack of innovation in the Peruvian mining sector in a preliminary way. We notice that the concentration of inward FDIs in the mining sector in low value added activities holds also for Latin America as a whole and for a small set of resource-abundant Latin American countries, namely Argentina, Bolivia, Brazil, Chile and Venezuela (for the sake of brevity, these data are not shown in this thesis and are available upon request).

Focusing attention on the Peruvian case, it is worth remembering that 47.8% of total inward FDI in all sectors is attracted in the mining sector from 2003 to 2014 on average. This suggests that nearly one half of inward FDI in Peru are concentrated in low value added activities along the mining value chain, with a low level of innovativeness.

To confirm the lack of innovation in the Peruvian mining sector even with FDI data, we calculate an inward FDI-based specialization index (RCA) for Peru concerning business (industry) activities, i.e. positioning along the GVC.

Following the same methodology of the previous section, we thus move to the investigation of specialization patterns of the Peruvian economy focusing on business (industry) activities involved by global FDI flows (Stollinger, 2019; Timmer et al., 2019). In particular, we exploit the information potential offered by fDi Markets dataset that allows distinguishing FDIs according to the business activity characterizing the projects. In this context, we learn about the technological, production and post-production activities along the GVC in which Peru is specialized, and more information about the business activities related to the mining sector. It is even possible to pinpoint the role played by the extractive, mining sector in contributing to such business activities' weight.

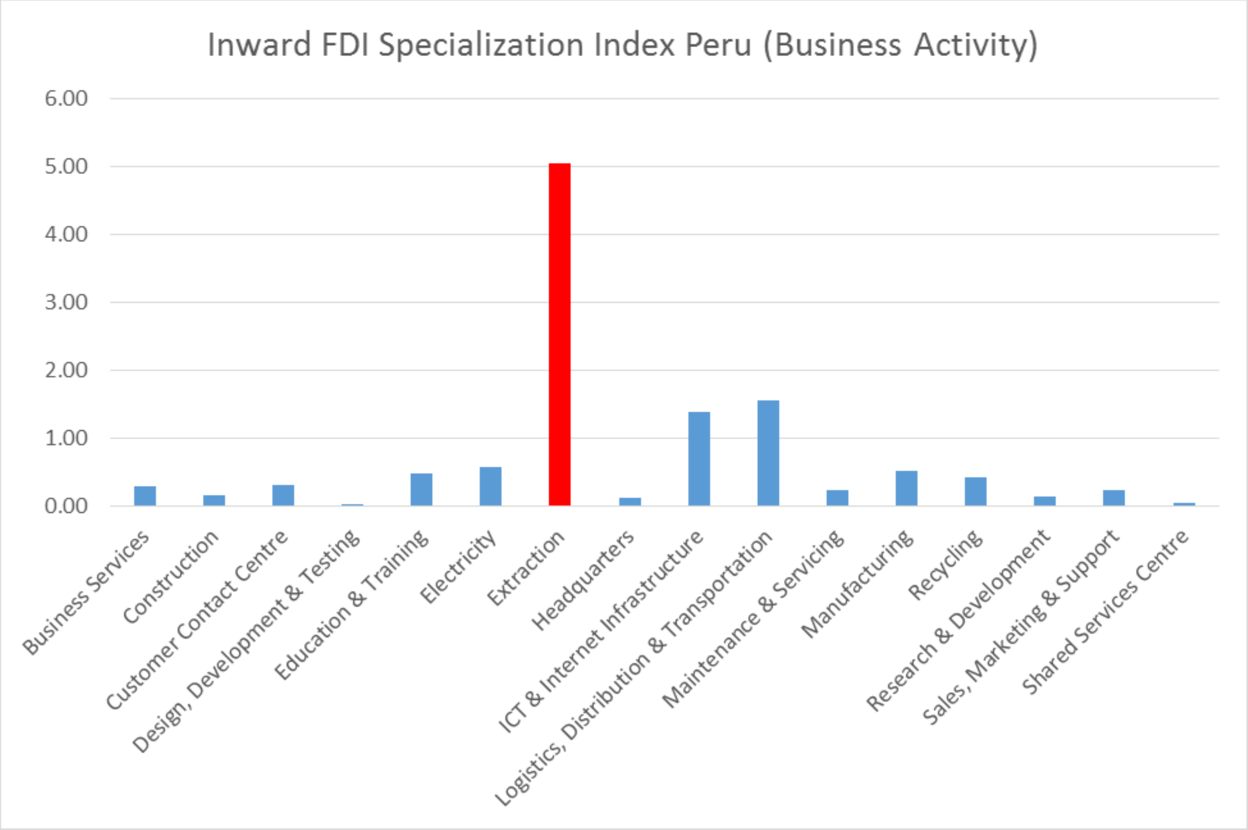
The inward FDI-based specialization index (i.e. RCA_IFDI_GVC) as an indicator or relative attractiveness of the *a-th* business activity for the *k-th* economy is adapted from the ratio described at the end of the previous section and is computed as follows:

$$\mathrm{RCA\_IFDI\_GVC}^{a}_{k} = \frac{\dfrac{FDI^{a}_{k}}{\sum k\ FDI^{a}_{k}}}{\dfrac{\sum a\ FDI^{a}_{k}}{\sum_{k} \sum_{a} FDI^{a}_{k}}}$$

Where the share of inward FDIs related to a given business activity received by a given economy (the numerator) is normalized according to the same share computed for the world as a whole, namely the global average (the denominator). This is a Balassa-like index (Balassa, 1965) computed in terms of inward FDIs instead of exports, and, in addition, the index reported here is defined on the basis of the value chain activity instead of industries (Zanfei, Coveri and Pianta, 2019).

Figure E5 portrays the results calculated for each business activity in Peru.

Figure E5 - Inward FDI-based specialization index computed for each business activity of the Peruvian economy (Capital Investment in Millions US$), 2003-2014 (average)



Source: Own elaboration on fDi Markets database.

Figure E5 indicates that Peru is specialized in ICT & Internet Infrastructure (a technological, high value added activity) and Logistics, Distribution & Transportation, a downstream and low value added activity along the value chain. The most important point is that Peru is over-specialized in the business activity "Extraction" with an inward FDI-based specialization index of 5.03, thus much greater than one. "Extraction" is a low value added business activity along the value chain. This confirms the presence of a structural weakness associated to specialisation in mining production, i.e. the lack of innovation in the Peruvian extractive sector. It is again confirmed, even using FDI data, that Peru does not exhibit a specialisation in innovation in the sector for which it is specialised in terms of production, thus raising development concerns.

In fact, the contribution of inward FDI in the mining sector (industry sector Metals) to the overall value of Extraction is of 82%; the contribution of the entire extractive sector (Metals + Coal, Oil & Natural Gas) is of 97%.

Weakness of institutions and social conflicts

From the beginning of the last decade, during the 2004-2009 commodity price boom, the Peruvian government enthusiastically embraced the new localism in natural resource management. Arellano-Yanguas (2011) argues that substantial revenues were delegated to sub-national governments, with a strong preference for mining areas. Legislation mandated participatory consultations on the use of these revenues locally. And civil society organisations and mining companies were positively encouraged to help sub-national governments to spend this money. The outcome, certainly throughout 2004-2008, has been perverse. The money has not been well spent. More strikingly, the incidence of "contentious politics" – local political disturbances and conflict – has increased in proportion to the extent of devolution of natural resource revenues to sub-national governments, which in turn, is directly correlated to mining company profits in the same region. This is true over both time and space. For the period 2004-2008 at least, there can be little doubt that the new localism in resource management caused increases in local political conflict. These local conflicts in turn triggered a broader wave of conflict throughout the country. However, we cannot automatically conclude that, because this led to conflict in Peru, it will inevitably do the same elsewhere. Context matters. Arellano-Yanguas (2011; p. 619) argues that three features of the political economy of contemporary Peru at least exacerbated the adverse effects of the new localist policies:

(i) The institutional weakness of the Peruvian central state and the fact that it is to a large degree captured by private business, with little capacity to represent other interests;

(ii) The weak participation of local political leaders in national politics, motivating them to pursue independent strategies and objectives, and to maximise resource transfers to their own localities;

(iii) The inability of the weak, "captured" central state to regulate or alleviate local conflicts between mining interests, diverse local economic interests, and competing local social and political movements. At least in the form and haste in which it was implemented, the Peruvian experiment with the new local policies was not well conceived.

It is worth noting that a set of institutional reforms and policy measures introduced since the 1990s have contributed to limiting the adverse effects of extractive industries that the country has experienced in its long mining tradition, but they have been less effective in unleashing the local potential benefits of mineral resource wealth (Ticci and Escobal, 2015).

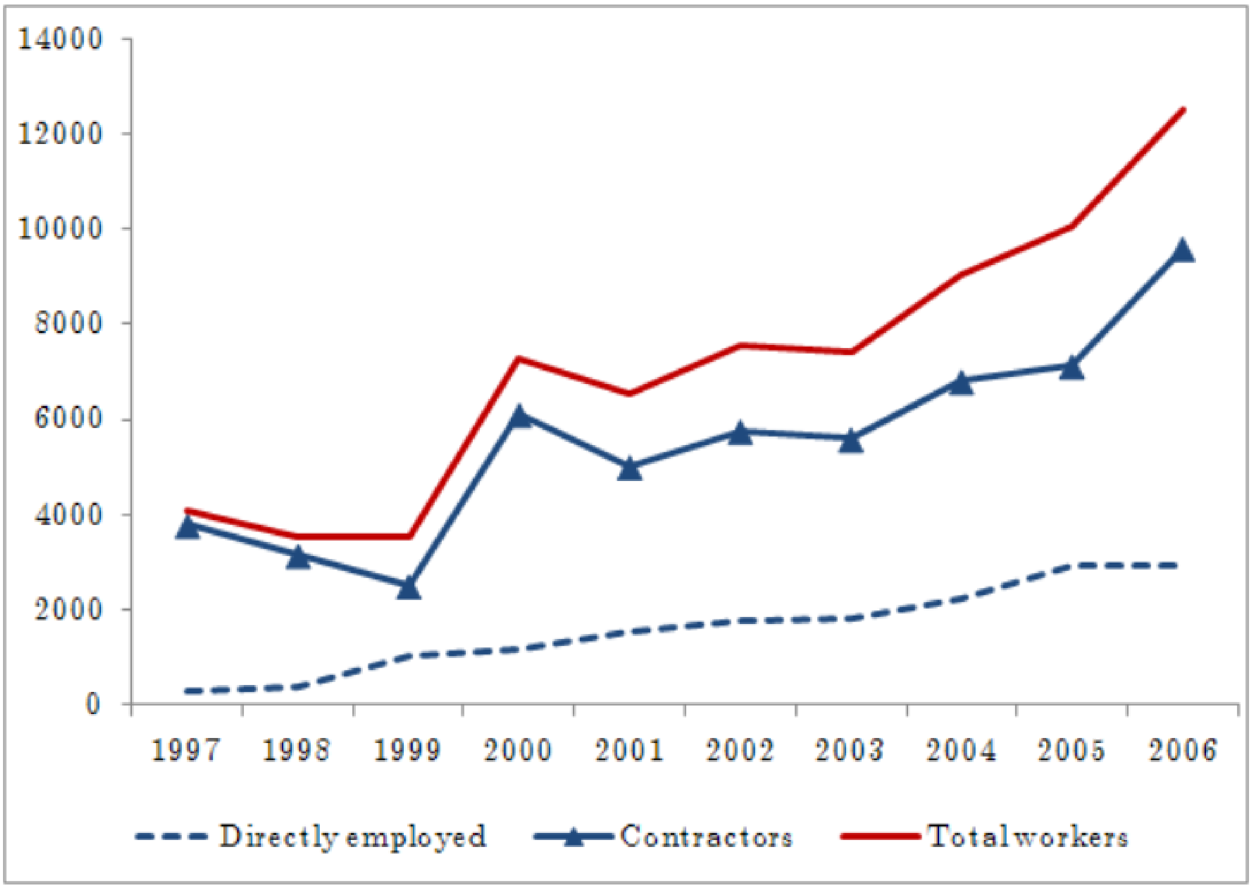
It seems that Peru has some troubles in terms of social conflicts, governmental issues, poor institutions and natural resources. This is a clear structural weakness that, together with the lack of innovation in the extractive sector and the lack of diversification of productive activities, may augment the risk of contracting the resource curse.

Pitfalls regarding local employment

We provide hints concerning some troubles with the creation of local employment through mining activities in Peru.

Figure E6 represents the evolution of the number of workers in a Peruvian gold mine, called Yanacocha; workers are directly employed by Yanacocha or indirectly hired through contractors.

Figure E6 – Direct and indirect employment related to the presence of the mining company Yanacocha in Peru



Source: Aragòn and Rud (2009; p. 24).

Aragòn and Rud (2009; p. 23) state that in the period 1997-2006 the number of total workers increased from 4,000 to 14,000, a substantial proportion of the active population of Cajamarca, a Peruvian town. To put these numbers in context, the mine's workforce represented around 12% of the active population of the city of Cajamarca in 2001 and 20% in 2005. Consistent with the mine policies, 60% of the workers are locals and almost all of them live in Cajamarca (Minera Yanacocha, 2006). The increase of mine employment occurred in 2000 and was driven mainly by workers indirectly hired through contractors. Contractor workers represent a significant proportion of the mine's workforce. On average, they represent 78.5% of the total mine workers. Workers directly hired by Yanacocha, tend to be skilled (e.g. engineers, accountants, technicians, secretaries, assistants, supervisors) as opposed to low-skilled workers employed through contractors. This is an exemplification of a structural weakness associated to natural resources that relates to the low quality of local employment created by mining activities.

As Weinstein and Partridge (2011) have noted, recent studies funded by extractive industries tend to overstate employment growth, while ignoring labour displacement from other sectors.

Some authors have questioned whether the influx of labour to work in developing mines is beneficial for the local economy (Deller and Schreiber, 2012). Cushing (1999) studied the Appalachian region of the

United States and found that many of the low skilled jobs in mines attract a labour force that may limit future economic growth, contribute to higher poverty rates and aggravate the resource curse.

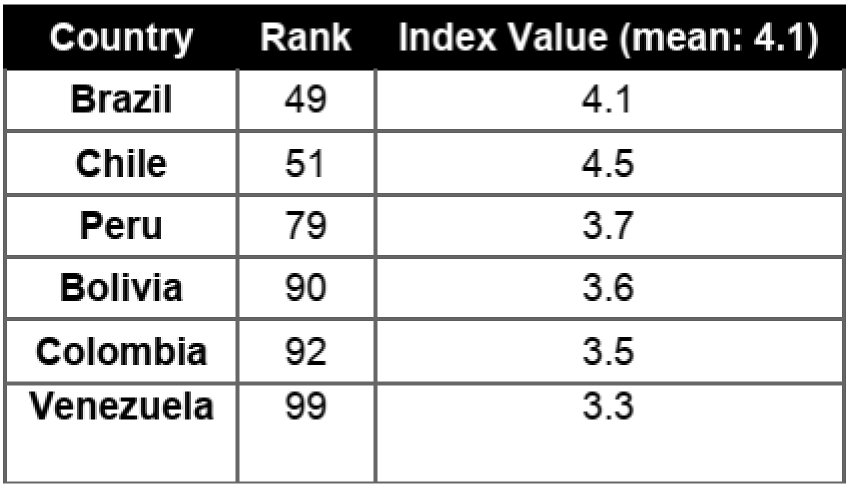
Environmental regulations

We have to emphasize the power of the mining companies over the state that is equally evident in the weakness of environmental regulation (World Bank, 2005). It is worth remembering that having weak environmental regulations may be one of the structural weaknesses that tend to be associated with natural resources production and it may lead to the extreme case of resource curse.

Arellano-Yanguas (2011) states that in Peru the Ministry of Energy and Mines is simultaneously responsible for: (i) promoting investment in new mining operations; (ii) granting mining concessions; and (iii) reviewing and approving the environmental impact assessments required for new exploration and extraction activities. These diverse responsibilities present conflicts of interest (Bebbington et al., 2007). However, Peru has gone from not having any kind of environmental regulation in the 1990s to turning down 20% of the proposed mining projects every year due to the unfulfillment of the social and environmental obligations (Molina, Olivari and Pietrobelli (2016; p. 12)).

To measure the level of stringency of environmental regulations, there is an index called Stringency of Environmental Regulation computed by the World Economic Forum (Molina, Olivari and Pietrobelli, 2016). The higher the rank and index value, the more stringent the regulation. Table E1 provides an exemplification of this index for some Latin American Countries, including Peru.

Table E1 – Stringency of environmental regulations in some Latin American countries



Country	Rank	Index Value (mean: 4.1)
Brazil	49	4.1
Chile	51	4.5
Peru	79	3.7
Bolivia	90	3.6
Colombia	92	3.5
Venezuela	99	3.3

Source: Molina, Olivari and Pietrobelli (2016; p. 40).

We notice that Peru performs better than Bolivia, Colombia and Venezuela and worse than Brazil and Chile. Overall, considering the recent strictness of the Peruvian environmental regulations towards mining companies, we cannot say that Peru shows this specific structural weakness.

Summing up

This short case study on Peru builds on some of the findings of Chapter 2 of this thesis summarised at the beginning of this case study. We have shown the worrisome presence of some structural weaknesses that associates with a strong specialisation in the extractive sector, and leads this developing resource-dependent country to resource curse risks.

We find that two thirds of inward FDIs from 2003 to 2014 are concentrated in the extractive sector in Peru. Moreover, Peru is "over-specialised" (and nearly "mono-specialised") in attracting inward FDI in the extractive sector, revealing a lack of diversification of its productive structure. Peru also exhibits a lack of innovation in the extractive sector, which reflects into a specialisation of FDIs in low value added activities along the GVC.

As already stated in Chapter 1 (the general introduction of this thesis) and confirmed in Chapter 2 of this thesis, the lack of diversification of productive activities and the lack of innovation in the extractive sector are two major structural weaknesses that associate to specialisation in natural resources, undermining natural resource-based development strategies. In other words, production specialisation without innovation specialisation gives rise to development concerns (Cimoli et al., 2006; Dosi and Tranchero, 2021).

Furthermore, institutions are weak and social conflicts related to troubles created by natural resources are present in Peru. Moreover, the quality of local employment created by mining activities is relatively scarce. These are two further structural weaknesses that associate to specialisation (dependence) in the extractive industry. Instead, Peru does not show any structural weakness regarding environmental regulations, considering that the Peruvian government has been adopting more stringent environmental regulations in regards to mining activities in modern times (Molina, Olivari and Pietrobelli, 2016).

Chapter 3

Identifying Technological Trajectories in the Mining Sector Using Patent Citation Networks[♦]

Abstract

We use patent citation networks to study technological change in the mining industry between 1970 and 2015. The analysis is further undertaken at the "sub-trajectory" level, by considering nine mining-related technological fields, i.e. sub-networks that represent the 9 technological sub-trajectories.

Consistent with previous literature focused on other technological domains, we find that innovation patterns are "technology bounded" in the mining sector, largely shaped by patenting activities carried out in a very limited range of mining technological fields, even though we detect a shift from exploration to environmental mining technologies (emergence of a new technological paradigm).

In addition, we examine two aspects of technical change that have been largely disregarded in extant research: the geographical patterns of inventive activities and the role of key applicants in such patterns. We show that core mining patents and leading inventors involved originate almost exclusively from the US, so that trajectories appear to be heavily geographically bounded, revealing that developing resource-abundant countries lag behind the technological frontier in mining. Moreover, only a few applicant firms are responsible for most inventive activities (oligopolistic structure), hence characterizing trajectories as "applicant bounded".

Similar results and implications are observed at the level of sub-trajectories, although with few exceptions.

Jel Codes: O31, 033, L72, F23, R11

Keywords

Technological trajectories; Technological sub-trajectories; Mining technologies; Geography of innovation; Patents; Development

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3.1 Introduction

As already stated in the previous chapters of this thesis, innovation in the mining sector is a crucial factor to make the specialisation in the mining sector a means of development, and not a "brake" on development. In this context, we examine innovation patterns in the mining industry. In particular, our goal is to figure out: how wide the range of innovations on the international technological frontier is; how wide the range of countries that lead innovation processes on the technological frontier is, and how wide the range of firms that play a role on the global mining technological frontier is.

Traditionally, innovation economists have not considered the mining sector to be very innovative (Bartos, 2007). According to this view, mining firms are more likely to be large and capital intensive in order to benefit from the economies of scale when facing demand that relies mostly, if not solely, on the price of mining commodities. Mining firms have few incentives to differentiate through product innovation or branding. Most innovations are related to cost-cutting processes, aiming to improve their narrow margins. As a result, mining firms source new technologies from their own production engineering departments or through technology embedded in products and services obtained from specialized suppliers (Pavitt, 1984).

Nevertheless, Daly, Valacchi and Raffo (2019) emphasize that there is compelling evidence to suggest not only that the mining sector is innovative, but also that, recently, it has become increasingly so. In most mining countries, this sector often contains a disproportionate number of innovative firms compared to other sectors (Arundel and Kabla, 1998). In addition, the sector has observed a dramatic increase in all innovation indicators since the early 2000s. This is reflected by the increasing importance of patents in the mining industry. There were more mining related inventions looking for patent protection in the last five years than all those accumulated from 1970 to 2000 (Daly, Valacchi and Raffo, 2019).

Encouraging innovation in the mining sector (Katz and Pietrobelli, 2018; Perez, 2015) and diversifying countries' productive structure (Hausmann and Hidalgo, 2009), mining might potentially replace manufacturing as a main source of development in developing resource-rich economies[40] (see Chapter 1 for a discussion on this). These are among the reasons why we chose to study mining innovation, from the perspective of technological change, not previously covered by the literature regarding this sector.

This paper examines the rate and direction of innovation and technical change in mining technologies as captured by patent citation networks. One of the most common approaches for evaluating the importance of (patented) innovations is to weight them using patent citations. Indeed, several studies have found that patent citations provide a reasonable "proxy" for their technological significance, as they generally appear to be highly correlated with other measures of the value of innovations such as assessments by technology experts (Jaffe and Trajtenberg, 2002).

The analysis of the connectivity of patent citation networks has important implications for assessing the relevance of innovations in large technical systems. In fact, it allows identifying technologically significant patents, the ones belonging to the main paths[41] of the citation networks. Another merit of this approach

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[40] Mining can be a very advanced sector using modern technology with high relative productivity, but its role in economic development frankly remains limited due to its small contribution in creating employment in comparison to the manufacturing sector (Haraguchi et al., 2017; Lavopa and Szirmai, 2018).

[41] A main path is a key knowledge flow related to the development of a technological field based on patent citations over a period of time (Chen, Shih and Liu, 2020).

is that, by reconstructing technological trajectories as sequences of patents, it opens the opportunity for a fruitful reconciliation between quantitative and qualitative insights in the study of technical change in specific domains, mining technologies in our case. Indeed, the approach allows to pin down a restricted number of patents, whose content can then be examined in detail. By reading the content of these patents, it is possible to reconstruct the heuristics governing inventive activities and go beyond the assessment of innovation patterns based only on patent counts (Fontana, Nuvolari and Verspagen, 2009).

In addition, Kalthaus (2019) points out that analyzing technological change at the sub-trajectory level can be a useful complement to considering overall trajectories, since significant innovation may be occurring at the sub-trajectory level that is not captured by the overall trajectory[42]. In other words, investigating sub-trajectories provides a broader understanding of sectoral innovation patterns.

We rely on main path analysis – a tool to capture and describe technological change - based on patent citation networks to identify technological trajectories and sub-trajectories in the mining sector across countries between 1970 and 2015.

As a first step in our analysis, we identify the technological trajectory for mining technologies across countries. Then, we split the network of mining patents (retrieved from the WIPO Mining Database and EPO-PATSTAT dataset for patent citations) into 9 sub-networks[43]. These nine sub-networks, corresponding to the nine technological fields into which mining technologies are divided, represent our 9 technological sub-trajectories. Each of the nine mining technological fields (sub-trajectories) is further divided into several technological sub-fields.

We use global (top) main path analysis which is a network method (for global search) proposed by Liu and Lu (2012) to identify technological trajectories. Global main path analysis is useful to identify major paths and critical bottlenecks which will eventually determine path dependent patterns of invention characterizing the evolution of mining technologies. In fact, it can often happen that main paths are "technology bounded", i.e. innovations influence each other sequentially and chronologically and tend to follow cumulative patterns within the boundaries of specific technological fields, limiting the possibility for other technologies to develop and/or affect a main path of technical change.

This normally reflects specific technological constraints and opportunities which condition improvements in extant technologies, direct research in specific directions and which lock out the choice of alternative technologies. By extracting the most significant sequence of patents, the structure of connectivity approach allows the identification of the key technological bottlenecks. In the case of mining technologies, technological change can be technology bounded if it happens that the trajectory unfolds only along very few mining technological fields (among the 9 ones) and the sub-trajectories unfold only along very few mining technological sub-fields. We find that technological change is technology bounded at the trajectory level and in most of the sub-trajectories.

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[42] Nonetheless, the approach to identify the sub-trajectories assumes that the path is completely internal, i.e. no technology from another sub-trajectory can impact upon the main path of a particular sub-trajectory.

[43] The nine sub-networks (sub-trajectories) within the mining sector are the following: environmental, automation, transport, exploration, blasting, mining (mine operation), processing, metallurgy and refining.

The existing literature on the topic of technological trajectories always focused on technology boundedness (see for instance Fontana, Nuvolari and Verspagen, 2007; Verspagen, 2009). We build on this literature by adding two relatively disregarded levels of analysis.

First, we examine to what extent inventive activities are also "geographically bounded", in terms of national sources (origin of applicants and inventors).

The idea is that the geographical diversification of innovation patterns may be limited by territorial proximity of inventors and by characteristics of national (and subnational) innovation systems, which may constrain the spatial distribution and scope of inventive activity.

Some studies have looked to give a geographical dimension to the evolution of technological paths, but generally within countries (see Nomaler and Verspagen, 2016 on technological trajectories within US counties). Our analysis on mining technologies will show a limited heterogeneity of inventive patterns in terms of geographical origin of applicants (firms) and inventors (almost exclusively from the US) concerning the "core patents" in the technological trajectory/sub-trajectories that provided technological change. This reveals a lack of innovation and the limits of developing resource-rich countries in providing technological advances. Relatedly, we will show that the knowledge related to the mining patents in the main path of the trajectory (and the sub-trajectories) does not diffuse across developing resource-abundant countries, considering that these patents are filed[44] in developed countries (again mostly in the US). Given the lack of developing and emerging economies in the production of frontier technology and given the limited diffusion of this knowledge to these countries, the extent of upgrading and technological development in mining in developing and emerging countries may be limited, with development consequences.

Second, we examine whether and to what extent technological change is also "applicants bounded", i.e. if there is heterogeneity in technological change in terms of type of applicants and most importantly across applicants within each applicant category. The question here is whether there may be some characteristics of firms or individuals which have first undertaken the inventive activity that can facilitate the control of subsequent inventions, thus excluding other inventors or applicants from taking part in the inventive process and in the appropriation of its economic value. If this was the case, there could be important consequences in terms of both the variety of innovation patterns, and of competitive effects associated to such patterns. As we shall see, the number of firms shaping the technological trajectories in mining is rather low, although some differences exist across sub-trajectories in this respect. Therefore, there seems to be a certain selectivity at the firm level (Verspagen, 2007). Therefore, certain firms help developing the trajectory and the way in which the trajectory develops may exclude some firms from entering and competing, leading to a narrow set of firms driving the trajectory. Then, one of the few ways in which new firms can enter is through the development of a new technological paradigm (Dosi, 1982), i.e. a movement from exploration to green technologies related to mining activities.

The paper is organized as follows. Section 2 provides an overview of the concepts of technological trajectories and sub-trajectories. Sections 3 and 4 describe, respectively, the data and methodology utilized. Section 5 illustrates the dataset (network) of mining patents. Section 6 identifies the technological

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[44] Knowing where patents are filed (protected) is an indicator of where their underlying technologies diffuse and are potentially used (Eaton and Kortum, 1999; Xu and Chiang, 2005; Hafner, 2008).

trajectory in mining technologies and provides an analysis of the portfolio of mining patents owned by the companies in the top main path of the trajectory. Section 7 identifies the nine technological sub-trajectories in mining technologies, highlighting analogies and differences with patterns observed at the trajectory level. Section 8 concludes.

3.2 Technological trajectories and technological sub-trajectories: conceptual backgrounds

Technological change unfolds along technological trajectories through the accumulation of knowledge and competences. A technological trajectory is the pattern of "normal" problem solving activity (i.e. of progress) on the ground of a technological paradigm (Dosi, 1982; Dosi and Nelson, 2013). In other words, the process of accumulation of technological knowledge occurs along trajectories of change that emerge over time in the search for better and better solutions to problems (Mina et al., 2007).

Dosi (1982) adds that it is important to interpret the process of technical change and innovation for several reasons, including to:

- define the "difficult puzzles" and unsolved difficulties of a technology which are often a necessary (although not sufficient) condition for the search for other ones;
- describe the transition from one technological path to another (i.e. discontinuities in the evolution of technologies) and assess the factors which allow the emergence of a "winning" technology.

The notion of a technological trajectory as outlined above points to technological innovations as sequential and interrelated events (Nomaler and Verspagen, 2021). One way to measure the interrelatedness between innovations that has been proposed in the literature (and is implemented in this paper) is by means of patent citations.

Patent documents contain a detailed description of the patented innovation. In addition to this, the name and address of the innovator and of the applicant are given. But most importantly for the present study, patent documents also contain references to previous patents, i.e. patent citations (Jaffe and Trajtenberg, 2002). It has been argued that a reference to a previous patent indicates that the knowledge in the latter patent was in some way useful for developing the new knowledge described in the citing patent (Verspagen, 2007). This is exactly the type of interpretation that allows us to use patent citations as a tool for mapping technological trajectories in mining technologies, going beyond the mere count of citations. We will take individual patents as pieces of knowledge and a presence of a citation to patent X in patent Y as an indication that patent Y builds upon patent X. Obviously, a single patent may source knowledge from multiple previous patents. In addition, citing patents may themselves become cited in the future, so that we will be able to map "chains" of knowledge as they develop over time.

Fontana, Nuvolari and Verspagen (2009) state that patent citations have been frequently used to measure the "importance" of a specific (patented) innovation. If a patent is cited very frequently, it means that the patent contains a "piece of knowledge" that forms the basis for several subsequent inventions. Hence, the patent in question ought to be regarded as "technologically" important. Empirical studies have generally confirmed the existence of a positive and significant relationship between the number of citations received by a specific patent and other indicators of technological and economic importance (Jaffe and Trajtenberg, 2002).

By looking comprehensively at the evolution of patent citations in a specific technological field, one is typically confronted with a network of patent citations. An intuitive interpretation of these networks is that they can be understood as representing the relationships between the pieces of knowledge contained in the individual patents. Following this reasoning, it should be possible to trace technological trajectories (Dosi, 1982) through the evolution of patent citation networks.

Technological trajectories are accumulated chains of incremental innovations that display the dominant long-run developments in technology (Nomaler and Verspagen, 2016). No single firm exclusively shapes a technological trajectory, although there may be cumulative phenomena leading to a concentration of patents in the hands of a few players which may indeed condition the development of such trajectories (see, e.g. Verspagen (2007) regarding fuel cells and the empirical evidence concerning technological trajectories in the mining industry that we will show in this paper).

While technological trajectories summarize the means to solve specific problems, sub-trajectories may be present inside a trajectory. Such sub-trajectories provide a similar solution, but via different means or with different performance characteristics (Durand, 1992). Kalthaus (2019) states that sub-trajectories provide opportunities for substantial improvements along the trajectory. At this micro level, dynamics can take place, such as the emergence of new sub-trajectories or shifts in the dominating sub-trajectory, which constitute and shape the development of the overall trajectory. It is worth emphasizing that, as in our case, sub-trajectories do not necessarily intersect with the overall trajectory.

Sub-trajectories can generate potential for improvements in or for widening the application space of a trajectory (Funk, 2003; Kash and Rycoft, 2000). Competition between different sub-trajectories can take place and technological lock-in into inferior sub-trajectories may emerge, hampering overall technological change. Revealing and understanding such technological dynamics at the sub-trajectory level can provide valuable insights into the innovation process, help us to understand drivers of technological change, and can be used to forecast future potentials and developments of trajectories (Kalthaus, 2019).

While the relevance of sub-trajectories seems compelling, economic analyses on the sub-trajectory level are scarce. In fact, the overwhelming majority of extant literature in this field does not make an intra-industry analysis at the level of sub-trajectories, neglecting possible important paths of technical change. Among the few studies that exist, Durand (1992) analyzes the development of sub-trajectories for insulin production, public switching in telecommunication, dynamic random access memory and semiconductors.

Certain sub-trajectories fail or do not improve as fast as other sub-trajectories (Durand, 1992). Sartorius (2005) points out that this lock-in situation can be overcome if policy support would not be technology neutral, but instead favors emerging sub-trajectories that show favorable characteristics and support their technological change. Otherwise, the accumulation of knowledge would increase the lock-in situation, while competition between the sub-trajectories would foster overall progress. As we will see, a similar situation of cumulativeness and path dependence happens for most of the sub-trajectories in mining technologies (but also at the trajectory level).

Extant literature concerning technological trajectories suggests that technical change may be technology bounded potentially leading to lock-in effects and/or to the exclusion of potentially promising developments due to constraints and bottlenecks affecting the direction of inventive activities (technological path dependence). This was previously implemented (using patent citation networks) to fuel cell technologies (Verspagen, 2007), coronary artery disease treatment technologies (Mina et al., 2007), data communication standards (Fontana et al., 2009), telecommunications switching industry (Martinelli, 2012) and environmentally friendly technologies in all industries (Nomaler and Verspagen, 2019). In this paper, we apply this line of argument to the mining sector to evaluate whether and to what extent such path dependencies can be observed over time at the trajectory and sub-trajectory level. In addition we will undertake a relatively novel research avenue as to figure out whether and how innovation patterns are geographically bounded across countries.

Moreover, we will examine the extent to which the same applicants (firms) concentrate in their hands the crucial patenting activities, hence selectively characterizing technological trajectories/sub-trajectories, and leading to "player or applicant bounded" trajectories.

We answer three main research questions related to technological change in the mining industry and development:

(i) To what extent are innovation trajectories in mining "Technology bounded"?

It can often happen that main paths are "technology bounded", i.e. innovations influence each other sequentially and chronologically and tend to follow cumulative patterns within the boundaries of specific technological fields (continuity), limiting the possibility of other technologies to develop and/or affect the main path of technical change (Nomaler and Verspagen, 2019; Nomaler and Verspagen, 2021). In the case of mining technologies, technological change can be technology bounded if it happens (for instance) that the trajectory unfolds only along very few mining technological fields (among the nine ones).

However, mining technologies that shape the trajectory may do so for long periods (a decade or more), but they can change over time from a mining technological field (at the aggregate level, i.e. in the case of the trajectory) or a mining technological sub-field (in the case of sub-trajectories) to another. This kind of discontinuity (Martinelli, 2012; Martinelli and Nomaler, 2008), if detected, breaks up the continuous and cumulative chain of an existing technological trajectory, implying a paradigmatic change (Dosi, 1982). Paradigmatic changes (i.e. technological paradigms) set boundaries and provide orientation for research and inventive activity to solve particular problems in a field (Dosi and Nelson, 2010).

(ii) To what extent are innovation trajectories in mining "Geographically bounded"?

Since the existing literature on the topic of technological trajectories has largely focused on point (i) (see for instance Fontana, Nuvolari and Verspagen, 2007; Verspagen, 2009; Kalthaus, 2019), we will undertake a relatively new research avenue to examine whether and how innovation patterns are geographically bounded across countries.

Specifically, we examine to what extent inventive activities are "geographically bounded", in terms of national sources (origin of applicants and inventors).

The idea is that geographical diversification of innovation patterns may be limited by territorial proximity of inventors and by characteristics of national (and subnational) innovation systems (Nelson, 1993; Edquist, 2005; Lundvall, 2007), which may constrain the spatial distribution and scope of inventive activity.

Our analysis on mining technologies will show a limited heterogeneity of inventive patterns in terms of geographical origin of applicants (firms) and inventors (almost exclusively from the US) concerning the "core patents" in the technological trajectory/sub-trajectories that provided technological change.

This would highlight a lack of capabilities of developing resource-rich countries in providing innovation and technological advances in mining, revealing a limited potential of that sector in contributing to development, even taking into account the lack of diffusion of these mining technologies across countries. In fact, sustained economic growth also requires constant technological improvements (Dosi and Nelson, 2013; Lavopa and Szirmai (2018; p. 61)).

The processes of knowledge accumulation and diffusion involve winners and losers, changing distributions of competitive abilities across different firms and, with that, changing industrial structures. Therefore, the patterns of growth of developed and developing economies are deeply shaped by the underlying patterns of technological and organizational evolution (Dosi and Nelson, 2010).

(iii) To what extent are innovation trajectories in mining "Player/applicant bounded"?

The third research question aims to explore the degree of heterogeneity in technological change in terms of type of applicants and most importantly across applicants within categories of applicants.

We will look at selectiveness at the firm-level (Verspagen, 2007) of the technological trajectory by asking whether the top main path we identify in the field of mining technologies are selective with regard to the organizations that have added to the paths. More specifically, we will ask whether those mining patents that we will identify as belonging to the top main paths in the development of mining technologies involve a limited selection of all organizations active in global mining innovation, or whether they are just a random sample of all organizations active in mining innovation. This is important to understand the nature of competition in innovation in the mining industry, considering that innovation and knowledge diffusion affect growth and survival probabilities of heterogeneous firms and, relatedly, that they are important determinants of industrial structure (Dosi and Nelson, 2013).

3.3 Data

We use patent citation networks to study the dynamics of technical change in the mining sector globally from 1970 to 2015.

The identification and interpretation of the technological trajectory and the technological sub-trajectories in the mining sector globally was made possible through the combination of information contained in the World Intellectual Property Organization (WIPO) Mining Database and in EPO-PATSTAT (for patent citations, titles and abstracts).

The WIPO Mining Database contains patents (at the global level) related to technologies concerning metallic and non-metallic minerals, and coal. Mining technologies are divided into 9 technological classes: exploration, blasting, mining (mine operation), processing, metallurgy, refining, transport, automation and environmental. Those technological fields are carefully selected on the basis of a patent search strategy[45] based on a combination of International Patent Classification (IPC) codes and keywords in PATSTAT (for details referring the patent search strategy, the description of each mining technological field and more see Daly, Valacchi and Raffo, 2019). These 9 technological classes frame the 9 technological sub-trajectories within mining technologies and they also stand for different stages along the mining value chain (see Appendix A for details on this).

It is worth pointing out that each mining technological field is further divided into some technological sub-fields (the sub-fields have been determined based primarily on how the IPC divides the technological fields; see appendix B for a list of them). The WIPO Mining Dataset also contains information, among others, about where the mining patents are filed (application authority), along with the geographical origin (at country level) of inventors and applicants.

The dataset is composed of 486,579 mining patents (nodes) that are connected to each other (largest component) through citations (edges).

3.4 Methodology: global main path analysis

Our method for identifying the trajectories and sub-trajectories in mining technologies is based on the methodology proposed by Hummon and Doreian (1989), and further developed by Liu and Lu (2012).

In this paper, the use of connectivity indicators and a search algorithm allow us to identify a set of patents connected by direct citations that constitute the main path, i.e. the main flow of knowledge within the network (Mina et al., 2007; Chen, Shih and Liu, 2020). These citations link subsequent problem-solving information and the underlying heuristics embedded in a patent show an ordered path of global, cumulative and irreversible technical changes (Martinelli, 2012). In this sense, the main flow of knowledge accomplishes the definition of technological trajectory put forward by Dosi (1982).

The patent citation network is directed (knowledge flows from the cited to the citing patent), and also acyclical (starting at one node of the network, a path can never return to that node). Two classes of nodes (patents) are of particular interest. A start-node is a patent that is cited, but does not cite any patents in the main path. An end-node is a patent that cites other patents, but is not cited itself (in the main path).

To identify technological trajectories and sub-trajectories, we proceed in two steps.

Firstly, we use the so-called Search Path Node Pair (SPNP) connectivity approach previously proposed by Hummon and Doreian (1989). SPNP[46] is a type of "traversal count" which measures the times a

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[45] The definitions of the nine mining technological fields are based on the mine lifecycle and supply chain (see Daly, Valacchi and Raffo (2019; pp. 7-8)) and stages in the mineral extraction process.

[46] For the sake of completeness, there exist other types of "traversal counts", e.g. Search Path Link Count (SPLC) and Search Path Count (SPC). There are small differences among them and extant literature on this field agrees on the fact that the outcomes are usually very similar implementing different types of traversal counts. We tried to weight our network of patent citations using those alternative traversal weights and we found similar results. The choice of a traversal count is rather subjective and often depends on the characteristics of a specific network (Liu et al., 2019). However, we chose to use the

citation link has been traversed if one exhausts the search from a set of start-nodes to another set of end-nodes. The logic behind using these traversal counts as the significance index is that if a citation link occupies a route through which much knowledge flows, it must have a certain importance in the knowledge dissemination-process. Furthermore, the nodes (patents) on the significant routes can also be inferred to possess important knowledge (Liu and Lu, 2012).

The "SPNP value" for the citation of patent *p* in patent *q* is obtained as follows. First, one needs to count all patents in the network for which a path to *p* exists (including *p* itself). Then, one has to count all patents that can be reached from patent *q* (including *q* itself). The SPNP value associated to the citation of patent *p* in patent *q* is thus the result of the multiplication of these two counts. It measures the number of pairs that can be formed by the patents "upstream" and "downstream" of the citation (Nomaler and Verspagen, 2016). Liu et al. (2019) state that weighting the network with traversal counts allows one to go beyond citation counts (direct measure), because it considers the effects of indirect citations between patents (see Appendix C for a thorough discussion on this). Thus, having a large number of citations is not a sufficient condition for becoming an important connection in the main flow of knowledge within the network (Fontana, Nuvolari and Verspagen, 2009). In fact, it is always possible to count the number of ties a patent has. However, this network approach allows us to enlarge this local perspective and to evaluate the whole citation structure (Martinelli and Nomaler, 2014). It is worth emphasizing that this explains why we obtain different results in the main path of the technological trajectory relative to the sub-trajectories.

Secondly, we develop the quantitative method of global main path analysis following Liu and Lu (2012). Our search algorithm for global main path analysis slightly differs from the priority first search algorithm as proposed in Hummon and Doreian (1989) that is a "local" approach. This "local" approach repeatedly chooses the link with the largest traversal count emanating from the current start-point. The overall sum of the traversal counts along the path identified via this approach may not be the largest among all the paths in the entire network (Lu and Liu, 2016). We propose to examine the "global" main path and we use it in the context of the mining sector. A global main path is the path that has the largest overall traversal counts. In contrast to the local main path that highlights the progressing significance of knowledge flows, the global main path emphasizes the overall importance in knowledge flow[47].

Specifically, we identify for every start-node in the network the path (ultimately leading to an end-node) that maximizes the multiplication (sum of logs) of the SPNP values along the path. Such a path is called "main path[48]".

SPNP traversal count because it tends to weight patents on the middle of a path more heavily, following Verspagen (2007), Fontana et al. (2009), Triulzi (2015), Nomaler and Verspagen (2019) and Nomaler and Verspagen (2021).

[47] The global main path adds to the analysis a new viewing angle for the significance of the main path. In practice, the local and global main paths may be identical or deviate only slightly.

[48] "The main path is thus a chain of citations that is constructed on the basis of some heuristic that aggregates the individual traversal weights of the constituent citation links of the chain. Usually, the main path is identified by a "priority first search" algorithm, which, starting from a given start-node, follow consecutive citation links stepwise, choosing each time the next forward citation link with the highest SPNP value until hitting an end-node. In case of a tie, the trajectory branches out since the algorithm separately takes each link with the highest link value and follows each emerging branch to the end" (Nomaler and Verspagen (2019; p. 7)).

Hence, our main path method identifies significant "links" rather than important "nodes". The nodes (patents) on the significant links are interpreted to nonetheless have certain importance.

Hummon and Doreian (1989) picked one start-node among several possible in their network, and focus on the main path that is formed by performing the priority first search algorithm from this start-node only (although they did sensitivity analysis comparing other start-nodes). If there are no ties, this method identifies a single trajectory, the top main path (TMP). Verspagen (2007) starts from each start-node in the network, and constructs (based on the "priority first search" principle) a collection of main paths that is referred to as the network of main paths (NMP). If the aim of the exercise is to describe the main trajectories in a specific technology field (as in our case of mining technologies), the choice is often to focus on the TMP, because the NMP remains too large to provide a concise evolution of technologies.

Nomaler and Verspagen (2019) argue that the NMP or TMP that is generated by the priority first search algorithm consists of a subset of citations and patents of the original citation network. This is obvious for the TMP, but even the NMP generally does not cover all patents and citations[49].

By its construction, the TMP connects the largest number of patents and it therefore represents the critical backbone of knowledge flow in the network (Martinelli, 2012). Furthermore, given its intrinsic cumulative and incremental nature, it is consistent with an empirical representation of a technological trajectory (Verspagen, 2007).

In the analysis, we begin by computing the TMP (global search) concerning the technological trajectory of the mining sector globally (entire network).

We then further split the network into nine sub-networks, which perfectly correspond to the nine mining technological fields discussed in the previous section. These nine knowledge areas in the network constitute the nine technological sub-trajectories in mining technologies and, for each of them, we identify the TMP (global search), to catch technological change that was not possible to be grasped at the trajectory level.

3.5 Global trends in mining innovation

In this section we provide some initial descriptive statistics on the composition of patents in mining and developments over time. In doing so, we pay attention to the three dimensions that we consider relevant when discussing technological trajectories, namely technological, geographical, and applicants.

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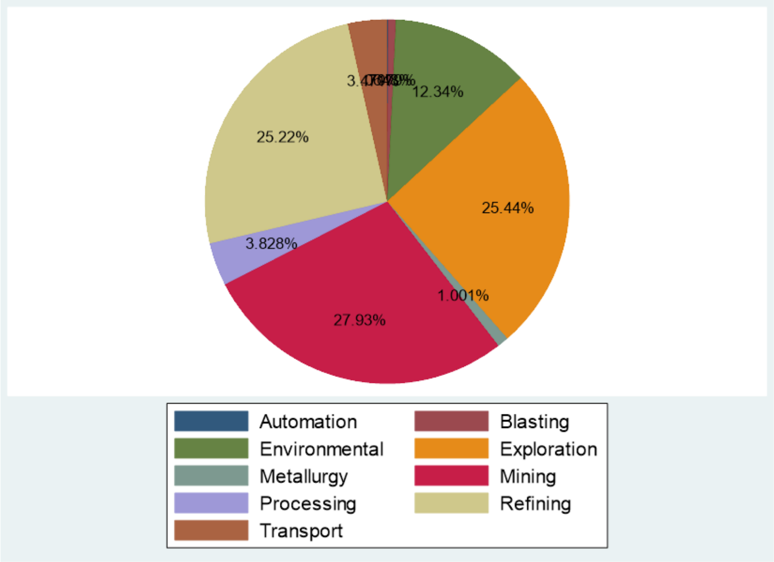
[49] Liu and Lu (2012) underpin that a potential problem that the (local and global) main path approach suffers is that the link with the highest traversal count may not always be included in the main path. To overcome this potential hurdle, the suggested solution is to view the main path as an extension of the most significant link and begin a search from both ends of the key-route rather from the sources. This is called the key-route search, which guarantees that this key-route is included in the main path (Lu and Liu, 2016). The key-route main path analysis would provide an enriched historical narrative, but it is also useful to control again for technology, geography and applicant "boundedness". Relatedly, we identified the key-route main path (Liu and Lu, 2012) for the technological trajectory in the mining industry as a robustness check and we found similar results to those obtained using global main path analysis (these findings are available upon request). Nevertheless, it is worth stressing that we decided not to explore the key-route path in the first place because one can lose the opportunity to observe other main paths and to clarify the priority of significance regarding the key knowledge flows as suggested by Liu and Lu (2012; p. 537). However, in order to avert (at least partially) the limitations of global main path analysis, we did split the network into nine sub-networks, i.e. the 9 mining technological fields (sub-trajectories) in the WIPO Mining Database, and we identified the TMP for each of them.

3.5.1 Technological perspective

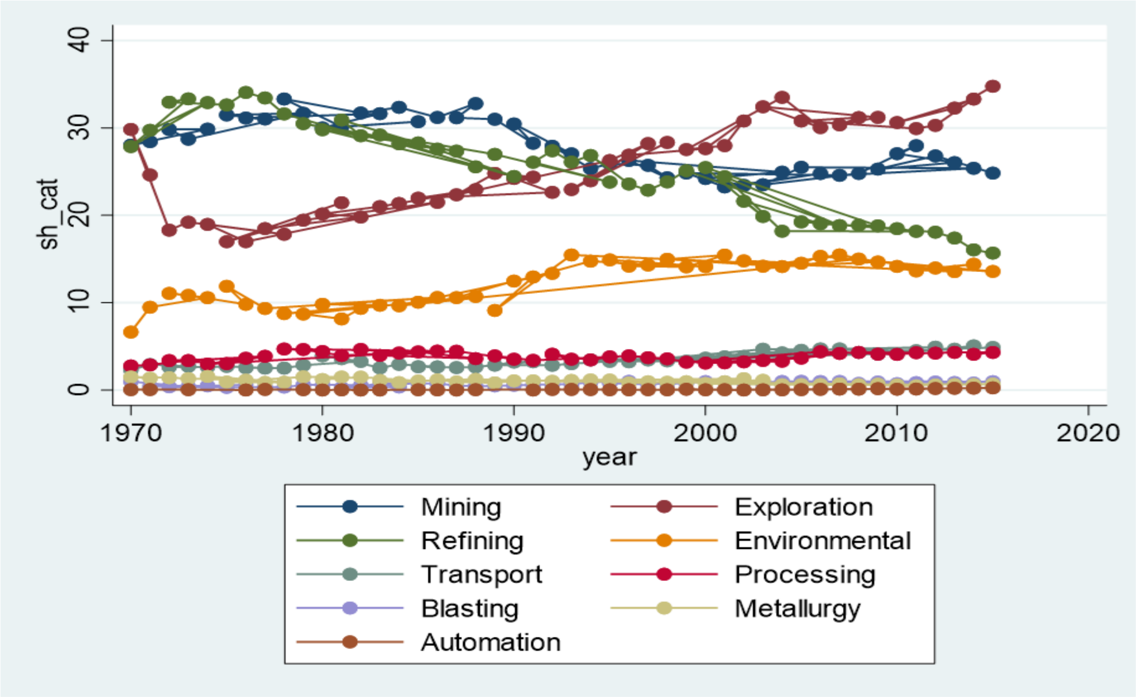
We begin by looking at the technological fields in which mining patents are taken out, in particular, considering the 9 technological fields (within mining) identified above. In Figure 1 we report information on both the share of patents over the period 1970-2015 in the different subfields and developments in patenting in these different subfields over time.

Figure 1 – Composition of and developments in patent families by mining technologies worldwide, 1970-2015

a) Share of patents in mining technological fields



b) Trends over time



Source: Own elaboration on WIPO Mining Database.

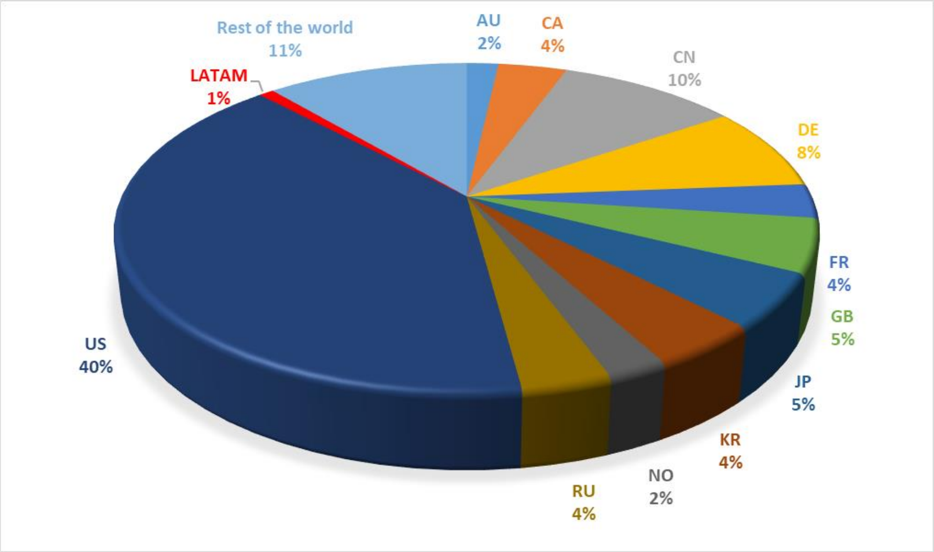
Figure 1a shows that the bulk of global mining innovation (90.8%) is concentrated in four mining technological fields: mining (mine operation) (27.9%), exploration (25.4%), refining (25.2%) and environmental (12.3%). The remaining 9% is distributed among processing (3.8%), transport (3.4%), metallurgy, blasting and automation. This suggests in a preliminary way the presence of a certain degree of technology boundedness in the whole dataset. Relatedly, we expect that the resulting technological trajectories follow a similar path.

When considering developments over time, Figure 1b shows that, in particular, after 1990, refining and mining show a declining trend. Daly, Valacchi and Raffo (2019) argue that putting less emphasis on improving refining methods may be a consequence of the declining quality of mined ores, which may make it inefficient to invest in new refining techniques. Firms may then prefer to dig new mines instead. Conversely, the extent of exploration, environmental and transport patenting have been increasing in the last decades. The exploration and transport trends are likely to relate to the industry's increasing need to discover new deposits in more remote locations in order to meet rising demand. Similarly, the increasing share of environmental technologies are probably linked with a wider social and industry awareness of the environmental impact of mining activities.

3.5.2 Geographical perspective

Considering that we are also interested in the geographical boundedness of mining patenting activity, we turn to consider where innovation and research activities are carried out, by identifying the country of origin of inventors (individuals).

Figure 2 – Share of mining patents in terms of inventor country of origin worldwide, 1970-2015



Note: "Rest of the world" represents all the other countries that are not labelled in the chart, with less than one percent each.

Source: Own elaboration on WIPO Mining Database.

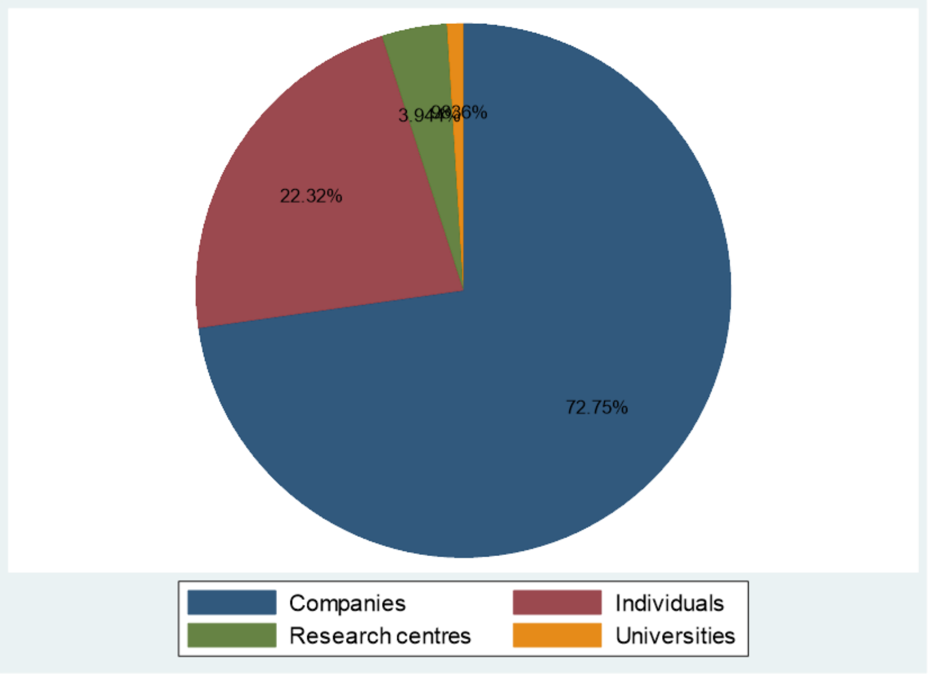
Being aware of inventors' country of origin is a good proxy for where innovation activities are carried out, which thus provides information about the potential for knowledge to be created locally (OECD, 2009). Results in Figure 2 reveal that inventors in the US play a dominant role (40%), followed by those in China (10%), Germany (8%), the UK (5%) and Japan (5%). France, the Republic of Korea, Canada and Russian Federation each account for a further 4% of global mining patents. It is worth stressing that there are some geographical areas, e.g. Latin America, that play a negligible role (1%) with regards to global mining innovation according to these data, despite these countries heavily relying on mining production (Iizuka, Pietrobelli and Vargas, 2019).

The descriptive results depicted in this figure provide preliminary evidence to state that mining innovation is geographically bounded, with innovation concentrated in few developed countries. In subsequent analysis, we will consider whether this geographical boundedness is also the case when considering the leading technologies, i.e. the patents that make up the technological trajectory, and to what extent.

3.5.3 Applicants' perspective

A third aspect of the dataset to be highlighted and linked to the analysis in the next sections is to ascertain the type of applicants that innovate and patent in mining technologies to control for applicant boundedness (see figure 3 below).

Figure 3 – Share of patent families in terms of type of applicant in mining technologies worldwide, 1970-2015



Source: Own elaboration on WIPO Mining Database.

Almost three quarters of applicants that innovate in mining technologies are companies, implying that it is likely that they also play a paramount role in shaping the technological trajectory and sub-trajectories. Just 22.2% of global mining innovation is carried out by individual inventors, with research centers (3.9%) and universities (1.1%) playing a negligible role.

In order to provide a benchmark for comparison to the TMP of the trajectory in the next section and to go more in detail about applicant boundedness in our dataset, Table 1 reports information on the main actors (applicants) in terms of global mining innovation (measured by patents).

Table 1 – Number of patents per company or organization in the mining patents database (largest component), 1970-2015

Rank	**Type of applicant***	**Organization name**	**Origin (country of residence)**	**Number of mining patents**	**Fraction of total**
1	C	HALLIBURTON	US	10923	2.24
2	C	SCHLUMBERGER TECHNOLOGY CORP	US	9427	1.94
3	C	BAKER HUGHES INC	US	6856	1.41
4	C	NIPPON STEEL CORP	JP	5376	1.10
5	C	SHELL OIL CO	US	3777	0.78

6	C	WEATHERFORD LAMB INC	US	2801	0.58
7	C	POSCO	KR	2669	0.55
8	C	JFE STEEL CORP	JP	2614	0.54
9	C	SUMITOMO METAL INDUSTRIES LTD	JP	2502	0.51
10	U	CHINA UNIVERSITY OF MINING & TECHNOLOGY XUYI R&DCENTER OF MINING EQUIPMENTS & MATERIALS	CN	2476	0.51
11	C	SMITH INTERNATIONAL INC	US	2361	0.49
12	C	KAWASAKI STEEL CORP	JP	2239	0.46
13	C	NKK CORP	JP	2214	0.46
14	C	ASIA OIL CO	JP	2116	0.43
15	C	SUMITOMO METAL MINING CO LTD	JP	1550	0.32
16	C	GEWERKSCHAFT EISENHUETTE WESTFALIA GMBH	DE	1523	0.31
17	C	PAUL WURTH SA	LU	1519	0.31
18	C	PETRO CHINA CO LTD	CN	1398	0.29
19	C	CHINA PETROCHEMICAL GROUP SHENG LI PETROLEUM ADMINISTRATION BUREAU DOWNHOLE OPERATION CO	CN	1237	0.25
20	C	EXXONMOBIL UPSTREAM RESEARCH CO	US	1178	0.24
21	C	MITSUBISHI HEAVY INDUSTRIES LTD	JP	1090	0.22
22	C	KAJIMA KENSETSU KK	JP	1054	0.22
23	C	TAISEI KENSETSU KK	JP	1046	0.21
24	U	CENTRAL SOUTH UNIVERSITY	CN	1039	0.21
25	C	SIEMENS AG	DE	972	0.20
26	C	DRESSER INDUSTRIES INC	US	970	0.20
27	C	M I LLC	US	960	0.20
		SUM OF ABOVE		73887	15.18
		OTHERS		412,692	84.82
		TOTAL MINING PATENTS IN THE DATABASE		486,579	100.00

*C = company; U = university.

Source: Own elaboration on WIPO Mining Database.

Table 1 documents all organizations in the database that hold more than 950 mining patents.

There are 27 organizations, i.e. 25 companies and 2 universities (out of 92,267 applicants in the entire dataset) with more than 950 mining patents, and together they account for about 15% of all patents in the database, implying a relatively high concentration in the data (applicant boundedness).

The fact that the top 27 organizations in mining innovation are almost entirely companies is coherent with Figure 3, since companies are the most active applicants in terms of mining patenting activity. We do expect "applicant" boundedness in terms of type of applicants even at the level of the trajectory and the sub-trajectories. We will also examine whether there is "applicant" boundedness within each applicant category in the resulting trajectories.

Overall, Japanese (37%), US (33%) and Chinese (15%) firms dominate the table, with relatively few companies from the Republic of Korea, Luxembourg and Germany being present as main players[50].

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[50] It is worth noting that the US dominates in terms of geography in Figure 2, but not their firms as shown in Table 1.

3.6 Technological trajectories in mining technologies: empirical results I

Following Liu and Lu (2012) and similarly to Hummon and Doreain (1989), we are interested in discovering the "main flows of knowledge" through a field of technological development (by means of a patent citation network), and confronting these flows with the notion of a technological trajectory[51].

This is the rationale behind Figure 4, starting from the right (earliest patent) to the left (latest patent). The intuition behind the top main path in Figure 4 is that it represents at each step (edge) the option that has attracted most weight in the SPNP procedure, i.e. it represents the largest flow of knowledge in the network.

Figure 4 – Top main path (technological trajectory) mining technologies globally, 1970-2015

Note: the number close to each dot (node, patent) in the figure is the application "id" attributable to the mining patent in question.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

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[51] It is worth remembering that we represent a patent citation network as a collection of vertices and edges. The vertices (mining patents) represent pieces of knowledge that depend on each other. The edges are connections between them, in this case citations between two patents. In the particular case of citation networks, the edges are directed, i.e. they have an origin (the cited patent) and direction (the citing patent). This convention corresponds intuitively to the idea of a piece of knowledge flowing from the earlier patent to the later patent.

Table 2 – "Core" mining patents present in the technological trajectory in chronological order starting from the right side to the left side of Figure 4

	appln_id	**Mining technological field**	**year**	**Type of applicant***	**Company name**	**Origin (country of residence)**	**Fraction of top main path (at company level)**	**Fraction of total patents in the dataset (486,579 patents) at company level**
1	50192276	Exploration	1970	C	**HALLIBURTON**	US	38%	2.24%
2	50327590	Exploration	1971	C	**SCHLUMBERGER TECHNOLOGY CORP**	US	10%	1.94%
3	49440011	Exploration	1972	C	**SCHLUMBERGER TECHNOLOGY CORP**	US	10%	1.94%
4	50689499	Exploration	1973	C	**HALLIBURTON**	US	38%	2.24%
5	52043285	Exploration	1975	C	**HALLIBURTON**	US	38%	2.24%
6	53342462	Exploration	1977	C	**HALLIBURTON**	US	38%	2.24%
7	53781978	Exploration	1977	C	**HALLIBURTON**	US	38%	2.24%
8	50729479	Exploration	1982	C	**HALLIBURTON**	US	38%	2.24%
9	51629128	Exploration	1983	C	**HALLIBURTON**	US	38%	2.24%
10	52097647	Exploration	1984	C	**HALLIBURTON**	US	38%	2.24%
11	54286746	Exploration	1986	C	**HALLIBURTON**	US	38%	2.24%
12	52555054	Exploration	1991	C	**HALLIBURTON**	US	38%	2.24%
13	46724083	Exploration	1993	I	SCHULTZ ROGER L	US	2%	0.01%
14	52985706	Exploration	1996	C	**BAKER HUGHES INC**	US	5%	1.41%
15	52822522	Exploration	1996	C	**BAKER HUGHES INC**	US	5%	1.41%
16	50517555	Exploration	1999	C	**HALLIBURTON**	US	38%	2.24%
17	52542436	Blasting	2000	C	MARATHON OIL CO	US	7%	0.04%
18	52542436	Blasting	2000	C	MARATHON OIL CO	US	7%	0.04%
19	53595253	Exploration	2001	C	**SCHLUMBERGER TECHNOLOGY CORP**	US	10%	1.94%
20	53769818	Exploration	2001	C	MARATHON OIL CO	US	7%	0.04%
21	45782958	Exploration	2001	C	**SCHLUMBERGER TECHNOLOGY CORP**	US	10%	1.94%
22	46669951	Exploration	2002	C	SENSOR HIGHWAY LTD	GB	2%	0.02%
23	49082647	Exploration	2002	C	**WEATHERFORD LAMB INC**	US	2%	0.58%
24	49788432	Exploration	2003	C	RENOVUS LTD	GB	2%	<0.01%
25	52454848	Exploration	2003	C	PRESSSOL LTD	CA	2%	<0.01%
26	54193053	Exploration	2004	C	**HALLIBURTON**	US	38%	2.24%
27	54393094	Environmental	2004	C	**HALLIBURTON**	US	38%	2.24%

28	50499431	Environmental	2006	C	**HALLIBURTON**	US	38%	2.24%
29	51251124	Environmental	2006	C	**HALLIBURTON**	US	38%	2.24%
30	57293019	Environmental	2008	C	**HALLIBURTON**	US	38%	2.24%
31	315600358	Environmental	2009	C	CALERA CORP	US	23%	0.04%
32	280654462	Environmental	2009	C	CALERA CORP	US	23%	0.04%
33	315801331	Environmental	2010	C	CALERA CORP	US	23%	0.04%
34	334494389	Environmental	2010	C	CALERA CORP	US	23%	0.04%
35	329618199	Metallurgy	2010	C	CALERA CORP	US	23%	0.04%
36	331626711	Environmental	2010	C	CALERA CORP	US	23%	0.04%
37	332946069	Environmental	2010	C	CALERA CORP	US	23%	0.04%
38	332398492	Environmental	2010	C	CALERA CORP	US	23%	0.04%
39	336476216	Environmental	2011	C	CALERA CORP	US	23%	0.04%
40	352232509	Environmental	2011	C	CALERA CORP	US	23%	0.04%
41	424896497	Environmental	2014	C	CARBONCURE TECH INC	CA	7%	<0.01%
42	442406948	Environmental	2015	C	CARBONCURE TECH INC	CA	7%	<0.01%
43	448177355	Environmental	2015	C	CARBONCURE TECH INC	CA	7%	<0.01%

*C = company; I = individual.

Note: companies that are also among the top 27 innovators in mining technologies at the global level (Table 1) are in bold.

Source: Own elaboration.

Figure 4 indicates that there are 43 mining patents present in the top main path. These 43 "core" mining patents are listed in Table 2. Table 2 informs us that patents regarding exploration technologies between 1970 and 2004 shape the TMP of the technological trajectory in mining technologies. Specifically, technological change was mainly focused on exploration technologies concerning surveying and testing of boreholes and wells. Between 1970 and 1996 (except for the year 2000 where we have two patents in blasting[52] technologies connected to the exploration phase), technological change in exploration mining patents changed, with a shift to production well telemetry systems and methods for automatically controlling downhole tools in response to sensed selected downhole parameters, as well as process and assembly for identifying and tracking assets, particularly tubes, equipment, tools and/or devices. In this manner, information that specifically identifies the asset may be compiled in a data base so as to maintain an accurate history of the usage of such assets[53].

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[52] The two patents in blasting technologies refer to methods and systems for performing a casing conveyed perforating process and other operations in wells (resource estimation) and are linked to exploration technologies (surveying and testing techniques).

[53] One important invention of the range of time in question (1996-2001) is patent No. 52822522 (year 1996) possessed by the US company Baker Hughes Inc, which is about production wells having permanent downhole formation evaluation sensors. A downhole control system for a production well is associated with permanent downhole formation evaluation sensors which remain downhole throughout production operations. These formation evaluation sensors may include, for example, neutron generator, gamma ray detector and resistivity sensors which can, in real time, sense and evaluate formation parameters including important information regarding formation invading water entering the producing zone. Significantly, this information can be obtained prior to the water actually entering the producing geological formation and therefore corrective action (i.e., closing of a valve or sliding sleeve) can be taken prior to water being produced. This real time acquisition of formation data in the production well constitutes an important advance over current wireline techniques in that the present invention is far less costly and can anticipate and react to potential problems before they occur. In addition, the formation

In the very latter part of this period (years 2003 and 2004) we further have three patents (exploration) related to drilling and methods and apparatus for drilling.

Considering the more recent period, from 2004 to 2015, the top main path of the technological trajectory in mining technologies became greener, with the path concentrating on environmental innovations linked to mining activities. Between 2004 and 2008, we observe four mining patents related to technologies for mitigation of climate change concerning mines/mining. Then, from 2009 to 2015, we have environmental mining patents regarding technologies related to mineral processing (except for patent 329618199 in the mining technological field "Metallurgy"[54]), which relate to technologies or applications for mitigation or adaption against climate change relating to the processing of minerals, i.e. the separation process of the minerals from the rocks after the extraction phase. Most of these patents refer to electrochemical methods of sequestering carbon dioxide (CO2). For instance, patent 315600358 is an invention bound to a low-voltage, low-energy electrochemical system and method of producing hydroxide ions and/or bicarbonate ions and/or carbonate ions utilizing significantly less than the typical 3V used across the conventional anode and cathode to produce the ions; consequently, carbon dioxide emissions attributable to the present system and method are significantly reduced.

To sum up, the evolution of mining technologies in the technological trajectory seems to reveal a discontinuity over time and follows some kind of coherence. In fact, at the beginning of the period technological change unfolded along exploration technologies that represent the basis to carry out mining activities, since the exploration phase is the initial stage of the mining value chain (see Appendix A). Then, technological change was directed to advanced mining technologies, i.e. environmental innovations that represent essential support services in the mining value chain, together with the technological fields transport and automation (Daly, Valacchi and Raffo, 2019).

3.6.1.1 Technology boundedness

Answering our research question (i) of whether the top main path is "technology bounded" or not at the trajectory level, it is noticeable that there is path dependence since innovations influence each other sequentially and chronologically, limiting the possibility of other technologies to develop. In the case of mining technologies, between 1970 and 2015, only 2 (exploration and environmental) out of 9 mining technological fields developed. As such, we can argue that technological change is technology bounded. Overall, as we have anticipated, along the top main path, we also detect a discontinuity over time consisting in a shift from exploration to green technologies. This can be associated to the emergence of a new technological paradigm (Dosi, 1982) that stems from the interplay of economic factors, institutional variables and unsolved difficulties regarding established technological paths. In the case of the mining industry, this "jump" is led by the need to address environmental challenges faced during mining activities (Humphreys, 2001; Iizuka, Pietrobelli and Vargas, 2019). We shall analyze below the role played by economic and institutional factors in the selection and establishment of those two technological paradigms.

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evaluation sensors themselves can be placed much closer to the actual formation (i.e., adjacent the casing downhole completion tool) than wireline devices which are restricted to the interior of the production tubing.

[54] The unique patent 329618199 in the technological field of "Metallurgy", among the environmental mining patents in the top main path of the technological trajectory is coherent to the unfolding knowledge flow, since it deals with electrometallurgy.

It must be said that this kind of technology "boundedness" reflects the key role played by exploration and environmental innovations in the mining industry.

The exploration stage is a costly, risky and delicate phase in mining activities both for local communities and for companies, especially in developing countries.

The average probability of success in mineral exploration is so low, and the attendant geological uncertainty so high that it has often been difficult for investors, managers and exploration geoscientists to actively manage for financial success (Eggert, 1993; Leveille and Doggett, 2006; Kreuzer and Etheridge, 2010). This likely contributes to an explanation for why technological change was focused on exploration technologies for decades in the technological trajectory (carried out by companies for reasons of techno-economic convenience).

It is worth pointing out the key uncertainties affecting mineral exploration:

(i) The inherent natural variability of geological objects and processes, which is a property of nature and exists independent of our geological investigations, e.g. uncertainty about the controls on the location of ore deposits, origin of mineralizing fluids, timing of deformation events, and nature of the tectonic setting (Kreuzer and Etheridge, 2010).

(ii) Conceptual and modern uncertainty (McCuaig, Kreuzer and Brown, 2007), which is linked to our incomplete knowledge and subjective interpretation of geological objects and processes. This type of uncertainty is almost impossible to quantify and subject to a well understood set of heuristics (metal short cuts and biases (systematic errors) (Tversky and Kahneman, 1974) that can cause severe and systematic errors of judgement (Welsh et al., 2005).

(iii) Errors that occur when we sample, observe, measure or mathematically evaluate geological data, and the propagation of these errors.

These uncertainties may help explain why innovation and technological change was dominated by exploration mining technologies for a large part of the period under consideration[55] (i.e. the presence of continuity and cumulativeness in that portion of the main path).

With regards to environmental technologies, it is worth pointing out that additional demands for innovation come from the social and environmental challenges faced by mining companies. Local communities are concerned with livelihood security, environmental degradation and the perception that the wealth created is not fairly shared. Governments react by introducing more stringent environmental regulations and requiring some local involvement in decision making (Benavente and Goya, 2011; Katz and Pietrobelli, 2018). Again, the demand for innovative solutions and sustainable methods of production is rising rapidly. Therefore, different to what happens in the case of technological change in exploration technologies, which seems to be led by reasons of techno-economic convenience of firms, the fact that

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[55] The uncertainties pinpointed in this context contribute to define the directions toward which the "problem solving activity" moves. The problem-solving activity determined by a paradigm can be represented by the movement of multi-dimensional trade-offs among technological variables which the paradigm defines as relevant. Progress can be defined as the improvement of these trade-offs (Nelson and Winter, 1977).

the trajectory became greener in the last decade is mostly policy driven at the level of national governments.

Andersen and Noailly (2019) state that the extraction and processing of metals (e.g. copper, gold, aluminum, iron, nickel), solid fuel minerals (coal, uranium), industrial minerals (phosphate, gypsum) and construction materials (stone, sand and gravel) is associated with air pollution, water contamination by toxic chemicals, landscape disruption and waste generation. Innovation in clean technologies, i.e. technologies aiming to reduce the environmental impact of mining operations, can provide an effective solution to address these environmental challenges (Humphreys, 2001). Innovative technologies can help to reduce water and energy consumption, to limit waste production and to prevent soil, water and air pollution at mine sites. Examples of such technologies are water-saving devices, electric haul tracks, desulphurization techniques to limit SO2 emissions and underground mining technologies to minimize land disruption (Hilson, 2002).

Clean technologies are characterized by a "double externality" (Jaffe, Newell and Stavins, 2005): first, just like all technologies, clean technologies generate knowledge spillovers (the knowledge externality) and second, they contribute to reducing the negative externality of pollution (the environmental externality). Due to this dual market failure, firms have few incentives to invest in clean technologies in the absence of government intervention and public policies are always justified to encourage the development of those technologies[56]. This likely contributes to confirm the fact that firms are compelled to innovate in environmental technologies by public policies.

3.6.1.2 Geography boundedness

Switching attention to the geographical dimension (answering research question (ii)), and focusing on the country of residence of the applicant as depicted in the penultimate column of Table 2), it can be observed that 86% of the "core" patents present at the trajectory level are from the US, 9% are from Canada and 5% are from UK applicants. The inventors of those mining patents are located almost exclusively in the US (90%), whilst the remaining 10% of inventors are Canadian. Thus, answering our research question (ii), technological change in mining technologies, in addition to being "technology bounded", is also "geographically bounded". It unfolds entirely on a limited geographical area, i.e. North America[57] for 95% of applicants and 100% of inventors.

It is worth emphasizing that the TMP of the technological trajectory is more geographically bounded than the overall mining patents in the dataset. In fact, in terms of country of residence of the applicant in the whole dataset, the US, Canada and the UK account for, respectively, 27.1%, 2.5% and 3.5% of total mining patents.

We also find that all the mining patents in the TMP of the technological trajectory are filed only in the US, revealing the absence of the related knowledge diffusion across countries.

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[56] An exception can be made for cost-saving clean technologies, such as energy-saving technologies. Profit-maximizing firms may have in this case incentives to innovate, even without policy intervention.

[57] In our study, North America includes USA and Canada.

This scenario confirms that developing resource-rich countries (e.g. Africa and Latin America) lag behind the technological frontier in terms of mining technologies. Dosi (1982) argues that if technical advances maintain their cumulative nature, and if oligopolistic structures (i.e. applicant boundedness portrayed in Table 2 and illustrated in the next section) tend to appropriate those technological leads, the process of technical change as such is not likely to yield to convergence between countries starting from different technological levels.

3.6.1.3 Player/applicant boundedness

In terms of applicants (research question (iii)), the top main path is shaped by 43 mining patents invented by companies[58] (except for patent No. 46724083 invented by one individual).

It is important to state that, between 1970 and 2015, only 11 applicants (10 firms and 1 individual) shape the technological trajectory; 71% of the TMP identified in the network is shaped by 3 US multinationals, i.e. Halliburton, Calera Corp and Schlumberger Technology Corp. In this sense, technological change in mining technologies is "applicants bounded" because there are very few big players responsible for the evolution of those technologies. Moreover, comparing the last two columns of Table 2, the dominance of the 11 players in the TMP of the trajectory is much stronger than in the whole dataset, revealing that the TMP is much more applicant bounded than the overall dataset.

It is worth stating that Halliburton and Schlumberger Technology Corp, in addition to being among the main players providing technological change in mining technologies, also rank first and second respectively in terms of global mining innovation (measured in terms of portfolio of mining patents, see Table 1). In other words, in addition to being the main players in the TMP, they are also major innovators in mining more generally.

A few companies[59] seem to be "dominant" in the sense of claiming ownership of the majority of the patents that lie on this fundamental path that we have identified in the network. This suggests that these companies seem to be strategically placed along the top main path of knowledge production and that the clustering not only reflects a general engineering logic, but also a logic based on the internal search strategy of a specific company.

The comparison between Tables 1 and 2 also confirms that our interpretation of selectivity at the firm-level (Verspagen, 2007) is present in the data: the network of the TMP involves indeed a selective set of patent holders. A small number of companies are found to play an important role in the TMP found in the analysis. It is worthwhile to note the fact that the same firms always shape the technological trajectory, i.e. applicant boundedness implies geography boundedness. Nevertheless, it must be stressed that the emergence of the new technological paradigm concerning green mining technologies has also been driven by (or led to the entry of) new innovators, i.e. Calera Corp and Carboncure Tech Inc.

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[58] This reflects player boundedness in terms of type of applicants involved.

[59] Analyzing the characteristics of the innovation process, most of the firms that are present in the TMP of the technological trajectory seem to belong to the "Schumpeter Mark II regime". Under the Mark II regime, innovative activities tend to be very cumulative and undertaken to a greater extent by a few incumbents which turn out to be "serial innovators" (Dosi and Nelson, 2010).

The presence of temporary monopolistic and long-run oligopolistic positions in providing innovation and technological advances in the mining sector is bound to affect the industrial structure and shape its transformation.

This oligopolistic structure may be due to difficulties faced by (applicants) firms in innovating in mining technologies, considering their costliness (among other hurdles). However, more generally, some other factors are at stake depending upon time spans. Specifically, in the earlier periods, when a technological paradigm emerges, oligopolistic positions mainly relate to dynamic economies (e.g. learning curves) and temporary asymmetries in relation to the capability of successfully innovating. In the second stage, when the mining technologies become mature within the paradigm, the origin of the oligopolistic structures might relate not only to the technological progressiveness of firms but also to some static entry barriers (e.g. economies of scale) (Dosi, 1982).

3.6.2 Portfolio of mining patents owned by firms in the top main path

Considering that 10 companies provided technological change in mining technologies along the TMP of the technological trajectory between 1970 and 2015, and some of them are also among the top 27 players in global mining innovation measured by patents (i.e. Halliburton, Schlumberger Technology Corp, Weatherford Lamb Inc and Baker Hughes Inc), we retrieved their mining patents' portfolio as a proxy for their innovation activities. In Table 3, we investigate the importance of mining innovation for these ten firms and we examine whether some firms are more present in the TMP of the trajectory than they are in patents more generally.

The two technological paradigms (exploration and environmental innovations) identified in Section 6.1 are also an "outlook" which focuses the eye and the efforts of technologists and engineers in defined directions. As Dosi (1982) suggests, we do believe that this might have interesting implications in terms of the sociology of the firms and it would be worth studying the origins and the backgrounds of "revolutionary" engineers (companies).

Table 3 – Portfolio of mining patents owned by the 10 companies in the TMP of the technological trajectory, 1970-2015

COMPANY NAME	Foundation year	Country of residence	No. PATENTS	Percent of total portfolios	Fraction of main path (at company level)
HALLIBURTON	1919	US	17,764	40.3	38%
BAKER HUGHES INC	1907	US	11,604	26.4	5%
SCHLUMBERGER TECHNOLOGY CORP	1961	US	9,475	21.5	10%
WEATHERFORD LAMB INC	1992	US	4,172	9.5	2%
MARATHON OIL CO	1887	US	414	0.9	7%
CALERA CORP	2007	US	355	0.8	23%
SENSOR HIGHWAY LTD	1996	GB	138	0.3	2%
CARBONCURE TECH INC	2007	CA	40	0.1	7%
PRESSSOL LTD	1910	CA	38	0.1	2%

RENOVUS LTD	1993	GB	33	0.1	2%
Total mining patents			44,033	100.0	

Note: for reasons of completeness, in this context the portfolio of mining patents of the firms present in the top main path (technological trajectory) is composed of all the patents possessed by each firm (not only patents that cite or are cited).

Source: Own elaboration on WIPO Mining Database.

Table 3 depicts that the companies that own the largest portfolio of mining patents are Halliburton, Baker Hughes Inc, Schlumberger Technology Corp and Weatherford Lamb Inc, with the rest having negligible portfolios in comparison to those four. Calera Corp, which does not own a huge portfolio of mining patents with respect to most of the others, has a quite important influence in fostering technological change in mining technologies in the TMP[60].

3.6.2.1 Geographical dimension

In this context, we identify which countries are users and producers of the mining technologies invented by the 10 companies in the TMP (We always refer to their patent portfolios, i.e. a total of 44,033 mining patents). We are particularly interested in examining to what extent these technologies have diffused to developing countries that have not generally been involved in innovation in the mining sector to any extent.

In terms of the geographical dimension, Figure 5 portrays where those multinationals have interests in filing their mining patents[61] across the globe, as a proxy for where they have potential interest in using their technologies and diffusing the patent-related knowledge (Eaton and Kortum, 1999; Hafner, 2008; Xu and Chiang, 2005). It turns out that almost one half of their patents are filed in the US (main technology user), 11% in Canada, 9% in UK, 7% in the European Patent Office, 7% in Latin America (especially Mexico, Brazil and Argentina), 6% in Norway, 5% in Australia, 2 % in China and 7% in the rest of the world.

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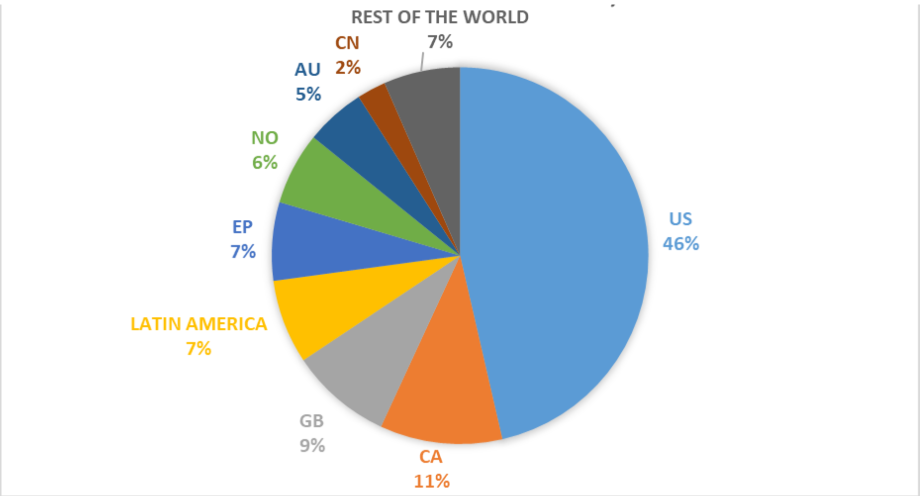
[60] The relatively small Calera Corp's portfolio of mining patents is probably because it was founded many decades later than the first three companies in Table 3.

[61] Patent portfolios representing 44,033 mining patents.

Figure 5 – Distribution of mining patents' portfolios of the 10 companies in the TMP of the technological trajectory in terms of application authority, 1970-2015

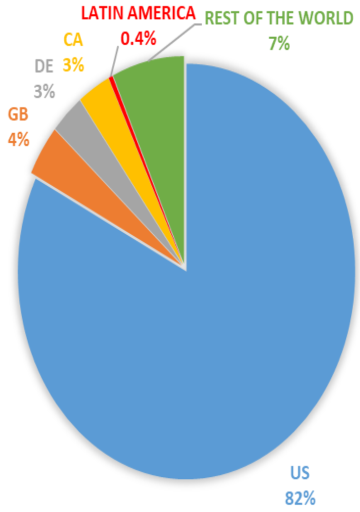


Note: "rest of the world" refers to the sum of the rest of the countries with less than 1% each.

Source: Own elaboration on WIPO Mining Database.

Switching attention to the inventors' country of residence of the 44,033 mining patents owned by the ten companies in the TMP (Figure 6), we check which countries are the main producers of their technologies (OECD, 2009).

Figure 6 - Distribution of mining patents' portfolios (share) of the 10 companies in the TMP of the technological trajectory in terms of inventors' country of residence, 1970-2015



Note: "rest of the world" refers to the sum of the rest of the countries with less than 1% each.

Source: Own elaboration on WIPO Mining Database.

Figure 6 tells something about the degree of internationalization of innovation of those 10 big players in technological change in mining technologies. It turns out that the bulk of their inventive activities are developed in the US (82%). Few inventors reside in the UK (4%), Canada (3%) or Germany (3%). No country has a significant impact except for the US in terms of knowledge created at the local level by those 10 multinationals.

In the previous section, we have learnt that technological change in mining technologies is geographically bounded in the sense that almost all the companies in the TMP are from USA, implying that developing resource-rich countries lag behind the technological frontier in mining.

Analyzing the portfolio of mining patents of those 10 "revolutionary innovators", it turns out that developing resource-rich economies (e.g. Latin America and Africa) are neither users (with the partial exception of Latin America) nor producers of their mining technologies. This confirms a lack of innovation in the mining sector, carried out in developing geographical regions (see also Figure 2 on this).

Specifically, 7% of the portfolio of mining patents owned by the 10 companies listed in Table 3 are filed in Latin America, where those firms have interests in using their patented technologies. However, if we focus on the inventors' country of residence, this percentage goes almost to zero. It means that those technologies that are potentially used in Latin America are not produced locally, but elsewhere. Therefore, Latin America is a technology user, but not a technology producer in mining (see also Chapter 2 on this). Africa is neither a user nor a producer of their mining technologies, considering that any patent is filed or invented there. The fact that no mining patents are filed in African countries (and only a few patents are filed in Latin America) might be related to the fact that there is no threat of imitation by potential competitors at the local level. Instead, the US is both a technology user and technology producer of their mining technologies, dominating both aspects in Figures 5 and 6.

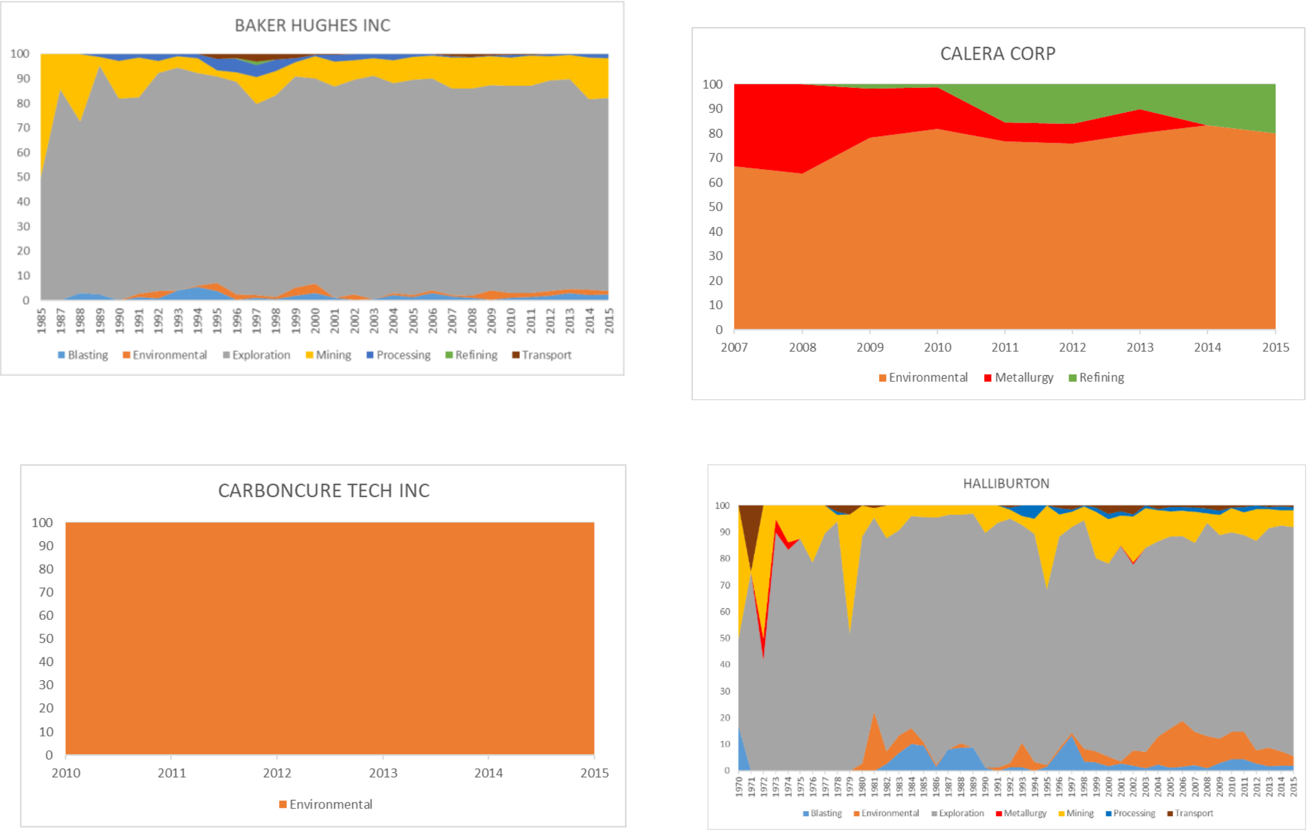
There seems to be "geography boundedness" even in terms of countries that use and produce the ten big innovators' technologies.

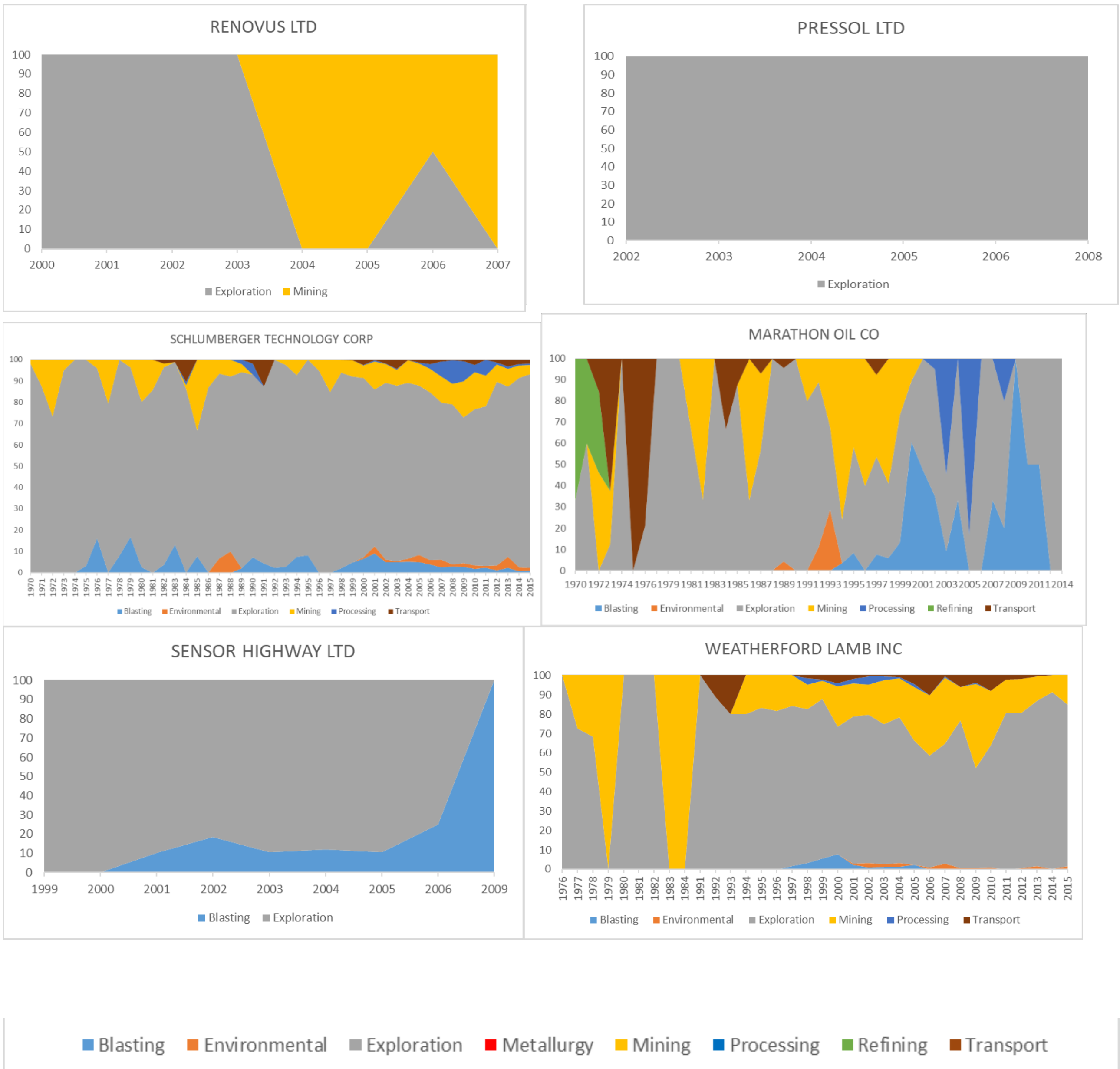
3.6.2.2 Technological dimension

This analysis, always concerning the portfolio of mining patents of the 10 firms (total of 44,033 patents) that characterize the top main path of the technological trajectory, is aimed at discovering how much their patenting activity is diversified in terms of mining technologies, i.e. the 9 mining technological fields in the WIPO Mining Database. In other words, we go to the firm level and we make some arguments as to whether their innovation (portfolio of mining patents) is focused on specific mining technological fields or whether they innovate broadly across the different fields. Furthermore, we make connections between innovation patterns of these companies and technological change at the level of the TMP (Figure 7).

We are convinced that investigating the technological history, i.e. the mining technological fields of expertise related to the "big innovators" in the TMP is one of the factors that are likely to operate as focusing forces upon defined directions of technological development. Precisely, we investigate whether the portfolios of mining patents are technology bounded and whether the firms have expertise in the mining technological fields in which they have patents in the TMP.

Figure 7 – Composition of portfolio of mining patents (share) owned by the 10 companies in the technological trajectory, in terms of mining technological fields (1970-2015)





Source: Own elaboration on WIPO Mining Database.

Figure 7 reports that around half of the ten companies have a quite diversified (and not technology bounded) patenting activity in mining technologies, namely Marathon Oil Co, Weatherford Lamb Inc, Halliburton, Schlumberger Technology Corp and Calera Corp. For the sake of accuracy, Marathon Oil Co seems to be the most diversified (and less technology bounded) company among the 10. Eight out of the 10 companies have a greater patenting activity in the exploration technological field, the exceptions being Calera Corp and Carboncure Tech Inc which mostly patent in environmental technologies related to mining activities. These latter two companies shape the top main path of the technological trajectory between 2009 and 2015 with mining patents in the environmental technological field. Thus, these two "new" firms drove a shift to a new technological paradigm[62]. In fact, they strongly contributed to making the trajectory greener, alongside Halliburton that has 5 environmental mining patents in the trajectory

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[62] Together with the economic interests of the organizations involved in R&D in these specific technological areas and institutional factors, e.g. public agencies (Dosi, 1982).

between 2004 and 2008. It is precisely in this period that Halliburton had its most intense patenting activity in the environmental technological field.

Only two companies are technology bounded and not diversified at all in terms of mining patenting activity concerning the 9 mining technological fields: Carboncure Tech Inc that has mining patents in environmental technologies only and Pressol Ltd that has mining patents in exploration technologies only.

We notice that the third mining technological field in which the firms are patenting more, after exploration and environmental, is mining (mine operation, e.g. extraction). This is coherent to the relevance of mine operation in the entire dataset (Figure 1a).

After the end of 1990s, Sensor Highway Ltd and Marathon Oil Co have a much stronger patenting activity in blasting. For the sake of coherence, Marathon Oil Co has two mining patents (year 2000) in the TMP in blasting technologies connected to exploration activities. In this case, this confirms again the fact that the direction of technical change reflects the field of expertise of a company.

3.7 Technological sub-trajectories in mining technologies: empirical results II

This section refers to the identification of the TMP of each of the nine technological sub-trajectories in mining technologies.

This exercise is undertaken to grasp technological change that cannot be ascertained at the trajectory level and to examine whether the TMPs are again technology, geographically and applicant bounded.

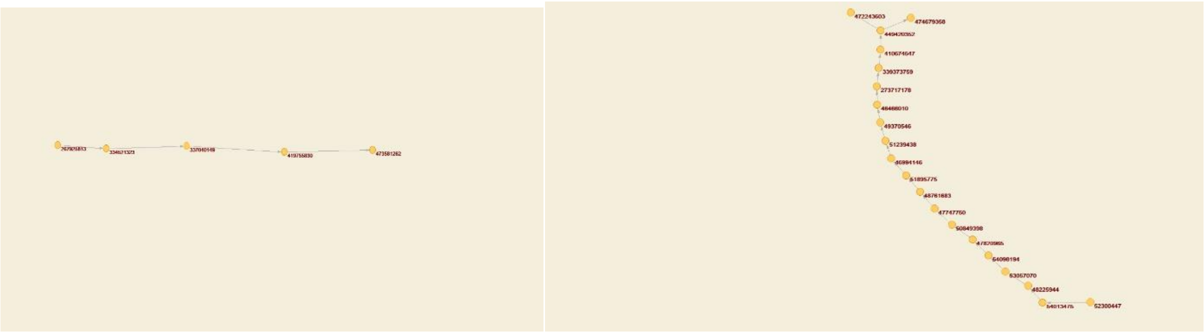
It is worth remembering that technological sub-trajectories do not need to intersect with the overall technological trajectory (Kalthaus, 2019), as it happens in our case. This means that the "core" mining patents in the TMP at the sub-trajectory level are totally different from the ones present at the trajectory level. It implies that sub-trajectories tell a different, additional story with respect to the trajectory.

Figure 8 portrays the findings related to the identification of the TMP related to each of the nine mining technological fields, i.e. technological sub-trajectories in mining technologies. The same methodology and the same rules expressed at the trajectory level in Section 6 hold for the sub-trajectories.

Figure 8 - TMP technological sub-trajectories in mining technologies globally[63], 1970-2015

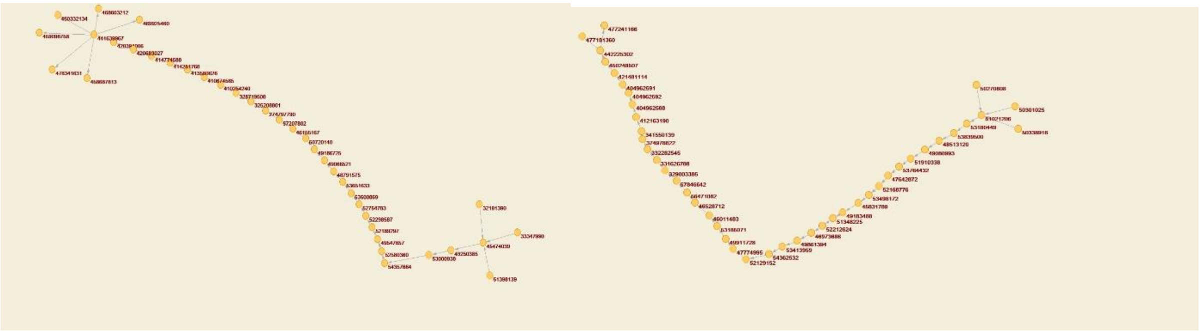
a) Automation

b) Blasting



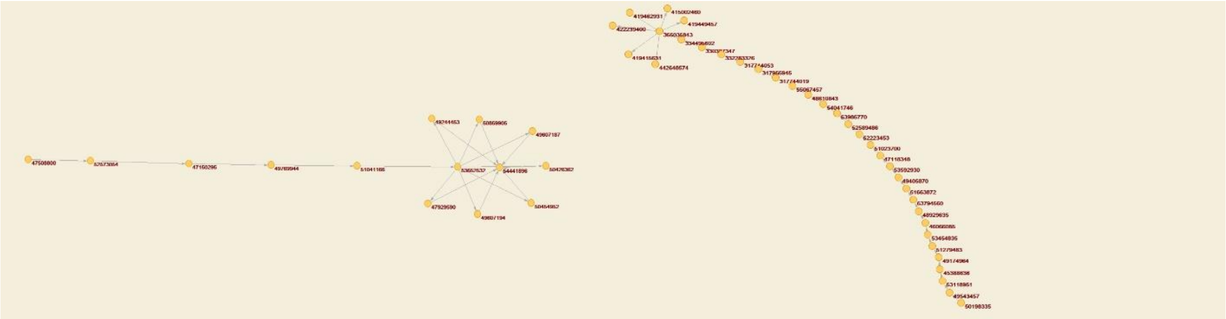
c)Environmental

d)Exploration



e) Metallurgy

f) Mining (mine operation)



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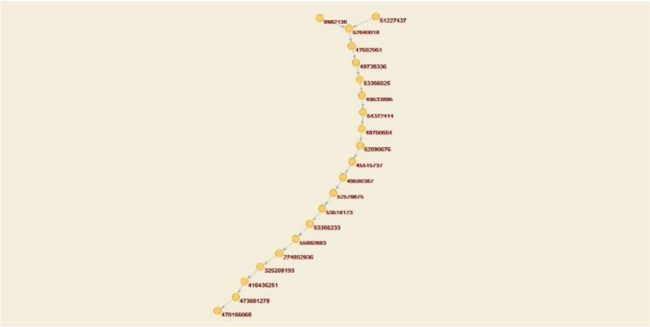
[63] All the main details (analytical version of results from global/top main path analysis) concerning the core mining patents of each of the 9 technological sub-trajectories (likewise to Table 2 at the trajectory level) are illustrated in 9 tables that are in appendix D.

g) Processing

h) Refining



i) Transport

Note: the number close to each dot (node, patent) in the figure is the application "id" attributable to the mining patent in question.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Some technological sub-trajectories developed more[64] than others, i.e. some mining technological fields have more mining patents in the TMP than others. In fact, there are more patents in the TMP of the exploration, environmental and mining (mine operation) sub-trajectories than in other cases. It seems to be coherent to the trend in the whole dataset (network), since these three mining technological fields are among the most influential in terms of patenting activity (see Figure 1).

Metallurgy and above all automation are the sparsest sub-trajectories, but they also have a negligible role in the entire dataset (Figure 1).

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[64] We exclude the automation sub-trajectory from the discussion of technology, geography and applicant boundedness because it did not develop enough to tell a narrative, since its technological change started very late (from 2009) with respect to the others and it is composed of only 4 mining patents in total. This circumstance is coherent to the fact that automation innovations represent less than 1% of global mining innovation (see Figure 1). For the sake of completeness, metallurgy is the second sub-trajectory that started to develop lately from 1998 and it stopped evolving on 2007.

3.7.1 Technology boundedness

First, we can provide comparisons between what happens at the trajectory level and at the sub-trajectory level[65]. In fact, it may sometimes happen that different technological paths emerge (Kalthaus, 2019). It is worth emphasizing that, when examining the presence of technological boundedness at the sub-trajectory level, we consider technologies, i.e. the mining technological sub-fields within each of the nine mining technological fields. For the sake of clarity, when identifying the TMP of each of the nine sub-trajectories (mining technological fields), we only consider mining patents within each specific sub-trajectory (mining technological field).

In the TMP of Figure 8d, an evolution of exploration technologies is notable that was not possible to grasp at the trajectory level. While the trajectory is mainly focused on exploration technologies regarding surveying and testing, the corresponding sub-trajectory reveals the presence of technological change totally characterized by drilling tools and methods and apparatus for drilling. This confirms the thesis according to which at the sub-trajectory level it is possible to grasp technological change that is not always visible at the trajectory level (Funk, 2003; Kalthaus, 2019; Kash and Rycoft, 2000).

Another difference that emerges between the trajectory and sub-trajectories concerns the environmental mining technological field; whereas technological change in the trajectory is mostly concentrated on technologies linked to mineral processing, at the sub-trajectory level (except for the very beginning) it unfolds along green innovations against climate change regarding mine operations.

It must be stressed that, since the two sub-trajectories in question, i.e. exploration and environmental evolve almost exclusively with regards to one mining technological sub-field out of the 7-9 potential and existent sub-fields (in the dataset) within these two technological fields[66], technological change is path dependent and again technology bounded. The same reasoning holds for the other four sub-trajectories: mining (mine operation), transport, processing and metallurgy. The only two sub-trajectories that seem not to be technology bounded are refining and blasting where, even though most of the "core" patents belong to the same mining technological sub-field, their content is quite diversified in terms of issues covered within the field (see Appendix E for details on this), against what happens in regards to the other sub-trajectories.

To sum up, 6 out of 8 technological sub-trajectories are technology bounded with the partial exception of refining and blasting.

3.7.2 Geography boundedness

As a second step, we consider the geographical dimension of technological change in mining technologies, i.e. understanding where it took place across the world at the level of each of the nine sub-

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[65] It is worth pointing out that there is no overlap in terms of the mining patents in the sub-trajectories and those appearing in the trajectory. Hence, our sub-trajectories reflect different lines of evolution of mining technologies.

It is worth remembering that each mining technological field is further divided into 7-9 mining technological sub-fields on average, with the exception of blasting and automation that have only one sub-field, and refining that has 3 sub-fields (see Appendix B and Daly, Valacchi and Raffo, 2019 on this).

[66] This section refers to geography by origin focusing on country of residence of the applicants (firms). However, for the sake of completeness, we provide a table in appendix F portraying the country of origin of inventors (individuals) that invented the "core" mining patents at the sub-trajectories level. The predominance of the US and the geography boundedness of the TMP of the sub-trajectories are again confirmed, with the partial exception of the Mine Operation sub-trajectory in this case.

trajectories. The exercise follows the same methodology of Section 6 for the technological trajectory which referred to the "main flow of knowledge" in the entire network. At the trajectory level, technological change was found to be geographically bounded since it is provided almost exclusively by US companies.

Answering our research question (ii), it turns out that the same geographical pattern is confirmed at the sub-trajectory level, with only few exceptions. Table 4 represents the geographical origin of the applicants that invented the "core" mining patents in the TMP of the sub-trajectories (column "TMP"); whereas, the column "overall patents" portrays the geographical origin of the applicants that invented the overall mining patents in each sub-trajectory (mining technological field). We examine whether the TMP is more geographically bounded than overall patents in each mining technological field (sub-trajectory).

Table 4 - Geographical concentration of mining patents per each sub-trajectory (i.e. mining technological field): TMP vs overall patents

SUB-TRAJECTORIES	**BLASTING**		**METALLURGY**		**REFINING**		**EXPLORATION**	
Geographical origin of applicants (firms)	TMP (18 mining patents)	OVERALL PATENTS (3,800 mining patents)	TMP (14 mining patents)	OVERALL PATENTS (3,948 mining patents)	TMP (21 mining patents)	OVERALL PATENTS (103,065 mining patents)	TMP (42 mining patents)	OVERALL PATENTS (135,090 mining patents)
	100% United States	54% United States	100% United States	20% United States	100% United States	13% United States	- 92.5% United States - 5% France - 2.5 The Netherlands	- 13% United States - 3.1% France - 0.75% The Netherlands
SUB-TRAJECTORIES	**ENVIRONMENTAL**		**MINING (MINE OPERATION)**		**TRANSPORT**		**PROCESSING**	
Geographical origin of applicants (firms)	TMP (32 mining patents)	OVERALL PATENTS (63,366 mining patents)	TMP (34 mining patents)	OVERALL PATENTS (127,764 mining patents)	TMP (21 mining patents)	OVERALL PATENTS (19,063 mining patents)	TMP (20 mining patents)	OVERALL PATENTS (18,953 mining patents)
	- 94% United States **- 6% Japan**	- 25% United States **- 21.3% Japan**	- 65% United States -21% Luxembourg - 5% Canada - 3% France - 3% The Netherlands **- 3% China**	- 19.7% United States - 0.07% Luxembourg - 1.5% Canada - 3% France - 1.1% The Netherlands **- 26.5% China**	- 72.5% United States - 10.5% Switzerland **- 4.5% Japan** - 4.5% Sweden - 4.5% Israel - 4.5% Canada	- 27.5% United States - 2.5% Switzerland **- 12% Japan** - 1.4% Sweden - 0.35% Israel - 1.7% Canada	- 40% United States - 30% China - 20% Canada - 10% Sweden	- 26.2 % United States - 29.5% China - 3.3% Canada - 0.7% Sweden

Note: the very few cases in which the geographical origin of the applicants is less prominent in the TMP than in patenting more generally are in bold.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Table 4 indicates that the TMP of three sub-trajectories, namely blasting, metallurgy and refining is completely shaped by US companies. Technological change in exploration and environmental sub-trajectories is almost entirely (more than 92%) from the US. Hence, the TMP of the blasting, metallurgy, refining, exploration and environmental sub-trajectories is geographically bounded, in the sense that technological change is molded by US companies, with the partial exception of the mining (mine operation), transport and (especially) processing sub-trajectories[67].

Table 4 also reports that the TMP of the sub-trajectories is more geographically bounded than the overall mining patents within each sub-trajectory (mining technological field). In fact, the US and non-US companies in the TMP are more prominent than in patenting more generally, with very few partial exceptions highlighted in bold in Table 4.

Further examining whether and to what extent the core mining patents in the TMP of each sub-trajectory diffuse across countries (Eaton and Kortum, 1999; Xu and Chiang, 2005; Hafner, 2008), we find again that the sub-trajectories are geographically bounded considered that their core mining patents are filed almost exclusively in the US (see Table G in Appendix G for details on this). Precisely, 100% of the core mining patents related to the blasting, exploration, metallurgy and refining sub-trajectories are filed only in the US. More than 90% of the mining patents in the TMP of the environmental and transport sub-trajectories are protected in the US. The only two sub-trajectories that are slightly less geographically bounded in terms of knowledge diffusion across countries of the mining patents in their TMPs are the mining (mine operation) and processing sub-trajectories, with a dominance of the US respectively of 88% and 70%.

3.7.3 Player/applicant boundedness

The third stage is to figure out whether technological change at the sub-trajectory level is "applicant bounded" (research question (iii)).

It is worthwhile to state that the overwhelming majority of applicants that bring technological change in mining technologies at the nine sub-trajectories level are firms (applicant boundedness in terms of type of applicants).

From the network analysis, within the "companies" applicant category, it turns out that only the processing and transport sub-trajectories are not "applicant bounded", considering that no firms seem to be dominant (except for the company "I Robot Corp" in the case of the transport sub-trajectory with 29.5% of the "core" mining patents).

The remaining six sub-trajectories (we exclude automation considering that it did not show an evolution) reveal a player/applicant "boundedness", since a small number of large companies (oligopolistic structure) shape the TMP of those sub-trajectories (see Appendix D).

Specifically, the sub-trajectory metallurgy is shaped by only one company, while just two out of the 14 firms that characterize the exploration sub-trajectory account for a 57% of core patents. One difference from the results at the trajectory level is that while the evolution of the trajectory in exploration

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[67] It is worth remembering a few successful cases of development through mining activities in both the developing (e.g. Botswana) and developed (e.g. Australia and Norway) world.

technologies is mainly due to the US oil company Halliburton, at the sub-trajectory level there is no trace of that company. The only company that is present both at the trajectory and at the exploration sub-trajectory level is the US company Baker Hughes Inc, although with different patents. This confirms the thesis according to which, identifying the sub-trajectories, different flows of technical change and different actors that determined it may emerge (Kalthaus, 2019). In other words, it turns out that the patents on the TMP of the trajectory do not appear in the main sub-trajectory.

In the case of the blasting, refining and environmental sub-trajectories, the TMPs are shaped by three companies, which account for 66%, 60% and 85% of core patents in these three sub-trajectories respectively. In the case of mining (mine operation), 4 out of 16 companies that appear in the top main path account for 61% of the core patents in this sub-trajectory.

Similar to the results at the trajectory level, results at the sub-trajectory level suggest that it is usually a small number of firms – and often the same firms – that shape the sub-trajectories, suggesting that applicant boundedness implies geography boundedness. In fact, we show that the sub-trajectories of processing, transport and mine operation are less applicant bounded and, as a consequence, the less geographically bounded (see Section 7.2).

We also find that the TMP of the sub-trajectories is more applicant bounded than overall mining patents for each sub-trajectory (see the last two columns of the tables in Appendix D for details on this).

3.8 Conclusion and ideas for future research

The findings in this paper indicate that, between 1970 and 2015, only two (exploration and environmental) out of nine different types of mining technologies developed on the technological frontier. Thus, we detect path dependence (cumulativeness) and technology boundedness at the trajectory level. However, this "continuity" is interrupted at the early 2000s, when a new technological paradigm (Dosi, 1982; Martinelli, 2012) emerges through a shift (discontinuity) from exploration to environmental technologies related to mining activities. The selection and establishment of these two technological paradigms (aimed at solving specific problems in an industry) is due to different reasons. Specifically, the focus on exploration technologies is led by economic interests of firms (reduction of costs and uncertainties); whereas, the development of environmental innovations at the trajectory level is motivated by institutional factors, i.e. stricter governmental policies aimed at coping with environmental challenges faced by the mining industry.

86% of the "core" patents present at the trajectory level are from US firms, with a further 9% from Canadian and 5% from UK firms. The inventors of these mining patents are located almost exclusively in the US. Thus, technological change in mining technologies, in addition to being "technology bounded", is also "geographically bounded". This reveals that developing resource-rich countries lag behind the technological frontier in mining. In addition, these core mining patents-related knowledge does not diffuse across countries, since they are filed only in the US.

71% of the Top Main Path (TMP) identified in the network is shaped by three US multinationals, i.e. Halliburton, Calera Corp and Schlumberger Technology Corp. Thus, technological change in mining technologies (at the trajectory level) is "applicant bounded" since a small number of large firms are responsible for the evolution of these technologies. There is selectivity at the firm level (Verspagen, 2007), i.e. a small number of companies is found to play an important role in the TMP found in the analysis.

It also turns out that the TMP of the mining trajectory is much more geographically and player bounded than the overall mining patents in the dataset.

We have developed an analysis concerning the origins and the backgrounds of the ten "Schumpeterian innovators" that characterize the TMP of the technological trajectory. We used their portfolio of mining patents as a proxy for it. It turns out that a very restricted group of developed countries (strong dominance of the US) is the producer and user of the mining technologies invented by these ten firms. There seems not to be any relationship with developing resource-abundant economies, with the partial exception of Latin America that uses some of their technologies.

Always from the analysis of the patent portfolios, we ascertain that around half of the companies engaged in producing core mining technologies have a quite diversified patenting activity in terms of the nine mining technological fields, revealing that their patent portfolio is not technology bounded. Instead, the rest of the companies in the TMP of the trajectory have a technologically bounded portfolio of patents. Moreover, the "core" patents present at the trajectory level reflect their main (mining) technological field(s) of expertise.

In Section 7, we have examined whether technological change is technology, geographically and applicant bounded at the level of the 9 mining sub-trajectories.

It is worth stressing that the environmental and exploration sub-trajectories showed a different evolution of technologies (within each of these fields) with respect to the environmental and exploration mining patents in the TMP of the trajectory.

Overall, the sub-trajectories are technology bounded because they evolve almost exclusively along one mining technological sub-field out of the several potential sub-fields (see Appendix B on this) within each sub-trajectory (i.e. mining technological field in the WIPO Mining Database). The only sub-trajectories that are less technology bounded are blasting and refining.

Furthermore, US applicants (companies) and inventors tend to dominate the "core" mining patents along the top main path of each sub-trajectory, with the partial exception of the mine operation, transport and processing sub-trajectories. We have also found that the mining patents in the TMP of the sub-trajectories are almost exclusively filed in the US, revealing a lack of their related knowledge diffusion across (developing resource-abundant) countries.

Given the lack of developing economies in the production of frontier technology and given the limited diffusion of this knowledge to these countries, the extent of upgrading and technological development in mining in developing countries may be limited, with development consequences[68].

All the sub-trajectories (TMP) are "applicant bounded", i.e. only one or very few companies shape them, except for the transport, mine operation and processing sub-trajectories that show a higher heterogeneity in terms of companies shaping the TMP.

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[68] Even taking into account its limited potential in creating employment, in comparison to the manufacturing sector (Haraguchi et al., 2017; Dosi and Tranchero, 2018).

We have realized that applicant boundedness implies geography boundedness at the sub-trajectories level. In fact, the sub-trajectories that are less applicant bounded (i.e. mine operation, transport and processing) are also less geographically bounded. Conversely, the sub-trajectories that are more applicant bounded (i.e. metallurgy, exploration, environmental, blasting and refining) are more geographically bounded than the remaining ones.

We also find that the TMP of the sub-trajectories is more geographically and applicant bounded than overall mining patents for each sub-trajectory.

If technical advances maintain their cumulative (although stochastic) nature, and if oligopolistic structures tend to appropriate those technological leads ("applicant boundedness" as it happens for mining technologies), the process of technical change as such is not likely to yield to convergence between countries starting from different technological levels. Imitative technological policies in this case may not be sufficient and public intervention aimed at catching-up might have to affect trade flows, foreign direct investment, and the structure of the national industry (Dosi, 1982).

We suggest three lines of future research regarding each of the aspects of "boundedness" investigated in this study:

- The technological trajectory is technology bounded and the technologies that shape the trajectory do so for long periods (a decade or more) but they change over time (from exploration to environmental innovations). In the TMP, it seems that the concentration on exploration technologies is due to reasons of techno-economic convenience of firms, whereas the focus on green technologies is mostly policy driven at governmental level. Future research could further analyze why there was this interesting shift from exploration to environmental innovations at the early 2000s, but also detailing the historical narrative at the trajectory level (and at the sub-trajectories level).
- It is worth studying the motivation behind geographically bounded trajectory and sub-trajectories (e.g. matter of national innovation systems that may constrain the spatial distribution and scope of inventive activity) that can fuel the still open debate regarding mining and development in developing resource-rich countries.
- A third line of future research can further investigate causes and consequences of player/applicant boundedness. It can be an issue of organizational constraints, dimension of firms and their research budgets. The presence of oligopolistic dynamics (very few big firms that invented the core patents in the TMP) risks ending up with a too limited competition in developing innovative processes of technical change in the mining industry.

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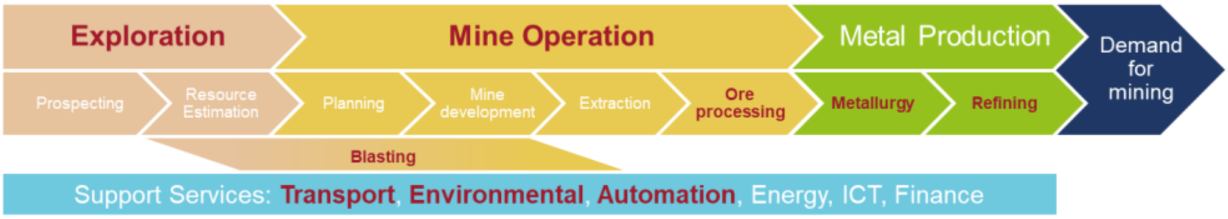
Appendix A Mining GVC stages

Table A – Simplified view of the lifecycle of a mine



Note: The mining sub-sectors presented in red text indicate the sub-sectors defined in the patent mining taxonomy.

Source: Daly, Valacchi and Raffo (2019; p. 7).

Appendix B List of mining technological sub-fields within each of the nine mining technological fields in the WIPO Mining Database

Table B – List of mining technological sub-fields within each of the nine mining technological fields in the WIPO Mining Database

Mining technological fields	**Blasting**	**Environmental**	**Processing**	**Refining**	**Metallurgy**	**Exploration**	**Mining (mine operation)**	**Transport**	**Automation**
Mining technological sub-fields	Fuses	Reclamation of mining areas	Crushing/grinding mineral	Ferrous	Metallurgy	Exploration	Ground control support	Rail	Automation
	Blasting	Treatment of waste water from metallurgical processes	Crushing/grinding	Non-ferrous	Pyro metallurgy	Surveying and testing-automatic control	Excavation	Rail infrastructure	
		Treatment of waste water	Flotation	Inorganic chemistry	Casting/powder metallurgy	Surveying and testing	Safety/rescue	Conveying	
		Biological treatment of soil	Separation		Furnaces	Core extraction	Shafts	Hoisting	
		Soil treatment	Processing		Coating	Methods or apparatus for drilling	Tunnels	Hauling	
		Waste disposal	Bio-processing (for bio-leaching of minerals)		Electrometallurgy	Drilling tools	Ventilation	Vehicles	
		Protection against radiation				Drilling	Subsea	Infrastructure	
		Environmental				Drilling-oil&gas	Mining (original)	Containers	
		Technologies related to mineral processing				Assays	Extraterrestrial	Control	

		Technologies related to metal processing					Mining (additional)	Shipping	

Note: for details regarding description of each of the mining technological sub-fields, see Daly, Valacchi and Raffo (2019; pp. 47-51).

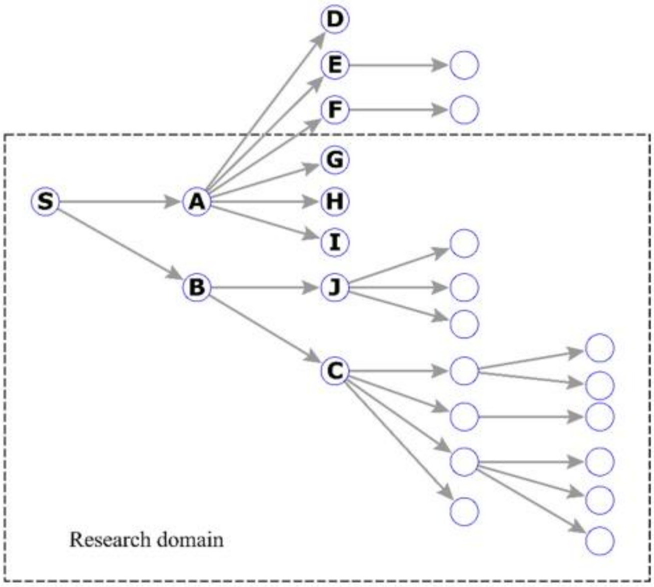
Source: based on Daly, Valacchi and Raffo (2019; pp. 47-51).

Appendix C The importance of indirect citations among patents

The sample citation network in Figure C stresses that a patent with a high citation count does not necessarily have a high SPNP value. Traversal counts (SPNP in our case) and citation counts are defined on different bases. If a patent is cited by many patents that do not belong to the dataset of the research scope, then these citations do not contribute to the traversal weight. For instance, patent A in figure C is cited by 6 patents, but citing patents D, E and F are out of the technological domain. They cannot contribute to the traversal weight of the link (S, A). Arrows in the figure point to the citing patents. Furthermore, if the citing patents do not attract further citations, then the traversal weight of a highly cited patent cannot be high (Liu et al., 2019).

Patent A's descendants G, H and I do not attract further citations, and so their contribution to (S, A)'s traversal weight is very limited. Conversely, a patent receiving a relatively low citation count may have a high SPNP value and is thus included in the top main path of the technological trajectory. This reasoning also applies to our case.

Figure C – A sample citation network



Source: based on Liu et al. (2019)

Appendix D “Core” mining patents on the top main path of the nine technological sub-trajectories

We report the “core” mining patents present in the top main path of the nine technological sub-trajectories in chronological order, referring to Figure 8

Table D1 – Environmental sub-trajectory

Environmental	**Appln_id**	**Mining technological sub-field**	**Year**	**Type of applicant ***	**Company name**	**Origin (country of residence**	**Fraction of top main path (at company level)**	**Fraction of total environmental mining patents in the dataset (63,487 overall patents) at company level**
1	32181390	Technologies related to mineral processing	1980	C	SUMITOMO OSAKA CEMENT CO LTD	JP	3%	0.15%
2	33347990	Technologies related to metal processing	1984	C	NIPPON JIRYOKU SENKO	JP	3%	0.06%
3	51398139	Technologies related to mineral processing	1983	C	TEXACO INC	US	3%	0.03%
4	45474039	Technologies related to mineral processing	1987	C	GEOCHEMICAL CORP	US	10%	<0.01%
5	49250385	Protection against radiation	1988	C	GEOCHEMICAL CORP	US	10%	<0.01%
6	53000938	Protection against radiation	1991	C	GEOCHEMICAL CORP	US	10%	<0.01%
7	54357664	Environmental	1992	C	**SHELL OIL CO**	US	3%	0.50%
8	52580360	Environmental	2000	C	B J SERVICES CO	US	3%	<0.01%
9	49547857	Environmental	2002	C	**HALLIBURTON**	US	50%	0.97%
10	52189297	Environmental	2003	C	**HALLIBURTON**	US	50%	0.97%
11	52298587	Environmental	2003	C	**HALLIBURTON**	US	50%	0.97%
12	52754783	Environmental	2003	C	**HALLIBURTON**	US	50%	0.97%
13	53500869	Environmental	2004	C	**HALLIBURTON**	US	50%	0.97%
14	53651633	Environmental	2004	C	**HALLIBURTON**	US	50%	0.97%
15	48791575	Environmental	2005	C	**HALLIBURTON**	US	50%	0.97%
16	49066521	Environmental	2005	C	**HALLIBURTON**	US	50%	0.97%
17	49186725	Environmental	2005	C	**HALLIBURTON**	US	50%	0.97%
18	50720140	Environmental	2006	C	**HALLIBURTON**	US	50%	0.97%
19	46155167	Environmental	2008	C	**HALLIBURTON**	US	50%	0.97%

20	57207802	Environmental	2009	C	**HALLIBURTON**	US	50%	0.97%
21	274797790	Environmental	2009	C	**HALLIBURTON**	US	50%	0.97%
22	325208801	Environmental	2010	C	**HALLIBURTON**	US	50%	0.97%
23	328719508	Environmental	2010	C	**HALLIBURTON**	US	50%	0.97%
24	410254240	Environmental	2012	I	BROTHERS LANCE E	US	25%	0.07%
25	410674565	Environmental	2013	I	BROTHERS LANCE E	US	25%	0.07%
26	413580626	Environmental	2013	I	BROTHERS LANCE E	US	25%	0.07%
27	414251768	Environmental	2013	I	BROTHERS LANCE E	US	25%	0.07%
28	414774588	Environmental	2013	C	**HALLIBURTON**	US	50%	0.97%
29	420683027	Environmental	2013	I	BROTHERS LANCE E	US	25%	0.07%
30	420394006	Environmental	2014	I	BROTHERS LANCE E	US	25%	0.07%
31	441639967	Environmental	2015	I	BROTHERS LANCE E	US	25%	0.07%
32	450332134	Environmental	2015	I	BROTHERS LANCE E	US	25%	0.07%

*C = company; I = individual.
Note: companies that are also among the top 27 innovators in mining technologies at the global level (table 1) are in bold.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Table D2 – Exploration sub-trajectory

Exploration	**Appln_id**	**Mining technological sub-field**	**Year**	**Type of applicant***	**Company name**	**Origin (country of residence)**	**Fraction of top main path (at company level)**	**Fraction of total exploration mining patents in the dataset (135,204 overall patents) at company level**
1	50270808	Drilling tools	1970	C	CHRISTENSEN INC	US	7%	0.15%
2	50301025	Drilling tools	1971	I	WILLIAMS E	US	2.5%	<0.01%
3	50338918	Drilling tools	1972	C	SHELL INTERNATIONALE RESEARCH MAATSCHAPPIJ BV	NL	2.5%	0.80%
4	51021206	Drilling tools	1974	C	HYCALOG INC	US	2.5%	<0.01%
5	53180449	Drilling tools	1976	C	CHRISTENSEN INC	US	7%	0.15%
6	53839500	Drilling tools	1977	C	CHRISTENSEN INC	US	7%	0.15%
7	48513120	Drilling tools	1980	C	NL IND INC	US	2.5%	0.08%

8	49080993	Drilling tools	1981	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
9	51910338	Drilling tools	1984	C	CDP LTD	US	2.5%	<0.01%
10	53764432	Drilling tools	1986	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
11	47642872	Drilling tools	1987	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
12	52168776	Drilling tools	1990	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
13	53498172	Drilling tools	1991	C	**BAKER HUGHES INC**	US	25%	4.32%
14	45831789	Drilling tools	1993	C	**BAKER HUGHES INC**	US	25%	4.32%
15	49183488	Drilling tools	1994	C	GENERAL ELECTRIC CO	US	5%	0.19%
16	51348225	Drilling tools	1995	C	DENNIS TOOL CO	US	2.5%	<0.01%
17	52212624	Drilling tools	1996	C	GENERAL ELECTRIC CO	US	5%	0.19%
18	46973686	Drilling tools	1998	C	**BAKER HUGHES INC**	US	25%	4.32%
19	49861394	Drilling tools	1999	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
20	53413959	Drilling tools	2001	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
21	54362532	Drilling tools	2001	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
22	52129152	Drilling tools	2003	C	ROCK BIT LP	US	2.5%	<0.01%
23	47774995	Methods or apparatus for drilling	2005	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
24	49911728	Drilling tools	2006	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
25	53185071	Drilling tools	2007	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
26	46011483	Drilling tools	2008	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
27	46528712	Drilling tools	2008	C	VAREL EUROPE SAS	FR	5%	0.03%
28	56471082	Drilling tools	2008	C	VAREL EUROPE SAS	FR	5%	0.03%
29	57846642	Drilling tools	2009	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
30	329003385	Drilling tools	2010	C	**SMITH INTERNATIONAL INC**	US	31%	1.52%
31	331626788	Drilling tools	2010	C	**BAKER HUGHES INC**	US	25%	4.32%
32	332282545	Drilling tools	2010	C	**BAKER HUGHES INC**	US	25%	4.32%
33	374978822	Drilling tools	2011	I	SCOTT DANNY E	US	2.5%	0.02%
34	341550139	Drilling tools	2011	C	**BAKER HUGHES INC**	US	25%	4.32%
35	412163190	Drilling tools	2012	I	BILEN JUAN MIGUEL	US	7%	<0.01%
36	404962588	Methods or apparatus for drilling	2012	C	**BAKER HUGHES INC**	US	25%	4.32%
37	404962592	Methods or apparatus for drilling	2012	C	**BAKER HUGHES INC**	US	25%	4.32%
38	404962591	Methods or apparatus for drilling	2012	C	**BAKER HUGHES INC**	US	25%	4.32%
39	421481114	Drilling tools	2013	I	BILEN JUAN MIGUEL	US	7%	<0.01%

40	450248507	Methods or apparatus for drilling	2014	C	**BAKER HUGHES INC**	US	25%	4.32%
41	442225302	Drilling tools	2015	I	BILEN JUAN MIGUEL	US	7%	<0.01%
42	477241166	Drilling tools	2015	C	**BAKER HUGHES INC**	US	25%	4.32%

*C = company; I = individual.

Note: companies that are also among the top 27 innovators in mining technologies at the global level (table 1) are in bold.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Table D3 – Metallurgy sub-trajectory

Metallurgy	**Appln_id**	**Mining technological sub-field**	**Year**	**Type of applicant***	**Company name**	**Origin (country of residence)**	**Fraction of top main path (at company level)**	**Fraction of total metallurgy mining patents in the dataset (3,952 overall patents) at company level**
1	47508800	Metallurgy	1998	C	TARGET TECH CO	US	100%	0.66%
2	52573054	Metallurgy	2000	C	TARGET TECH CO	US	100%	0.66%
3	47150295	Metallurgy	2002	C	TARGET TECH CO	US	100%	0.66%
4	49769944	Metallurgy	2003	C	TARGET TECH CO	US	100%	0.66%
5	51041166	Metallurgy	2003	C	TARGET TECH CO	US	100%	0.66%
6	53652532	Metallurgy	2004	C	TARGET TECH CO	US	100%	0.66%
7	47929590	Metallurgy	2005	C	TARGET TECH CO	US	100%	0.66%
8	49607194	Metallurgy	2005	C	TARGET TECH CO	US	100%	0.66%
9	49607187	Metallurgy	2005	C	TARGET TECH CO	US	100%	0.66%
10	50859905	Metallurgy	2006	C	TARGET TECH CO	US	100%	0.66%
11	49244453	Metallurgy	2006	C	TARGET TECH CO	US	100%	0.66%
12	50426362	Metallurgy	2006	C	TARGET TECH CO	US	100%	0.66%
13	50454952	Metallurgy	2006	C	TARGET TECH CO	US	100%	0.66%
14	54441896	Metallurgy	2007	C	TARGET TECH CO	US	100%	0.66%

*C = company.

Note: companies that are also among the top 27 innovators in mining technologies at the global level (table 1) are in bold.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Table D4 – Mining (mine operation) sub-trajectory

Mining (mine operation)	**Appln_id**	**Mining technological sub-field**	**Year**	**Type of applicant ***	**Company name**	**Origin (country of residence)**	**Fraction of top main path (at company level)**	**Fraction of total mine operation mining patents in the dataset (127,879 overall patents) at company level**
1	50198335	Excavation	1970	C	HEATH & SHERWOOD DRILLING LTD	CA	3.3%	<0.01%
2	49543457	Excavation	1972	C	ESSO PRODUCTION RESEARCH	US	3.3%	0.06%
3	53118951	Excavation	1976	C	WONDER PRODUCTS CO	US	3.3%	<0.01%
4	45388636	Excavation	1979	C	HYDRIL CO	US	12%	0.08%
5	49174964	Excavation	1981	C	HYDRIL CO	US	12%	0.08%
6	51279483	Excavation	1983	C	HYDRIL CO	US	12%	0.08%
7	53454835	Excavation	1985	C	HYDRIL CO	US	12%	0.08%
8	46066085	Excavation	1987	C	XL SYSTEMS	US	3.3%	<0.01%
9	48929635	Excavation	1988	C	KHAJDRIL KO FIRMA	US	3.3%	<0.01%
10	53794560	Excavation	1992	C	MARUBENI TUBULARS INC	US	3.3%	<0.01%
11	51663872	Excavation	1995	C	VALLOURECOIL & GAS	FR	3.3%	0.03%
12	49405870	Excavation	1999	C	JOHN GANDY CORP	US	3.3%	<0.01%
13	53592930	Excavation	2001	C	GRANT PRIDECO LP	US	3.3%	0.06%
14	47118348	Excavation	2002	C	ENVENTURE GLOBAL TECH	NL	3.3%	0.09%
15	51023700	Excavation	2003	C	**WEATHERFORD LAMB INC**	US	14%	0.40%
16	52223453	Excavation	2003	C	**WEATHERFORD LAMB INC**	US	14%	0.40%
17	52589486	Excavation	2003	C	**WEATHERFORD LAMB INC**	US	14%	0.40%
18	53985770	Excavation	2004	C	**WEATHERFORD LAMB INC**	US	14%	0.40%
19	54041746	Excavation	2004	C	**WEATHERFORD LAMB INC**	US	14%	0.40%
20	48610843	Excavation	2005	C	GRINALDI LTD	US	3.3%	<0.01%
21	55067457	Excavation	2008	C	TENARIS CONNECTIONS LTD	LU	19.1%	0.07%

22	317744019	Excavation	2009	C	TENARIS CONNECTIONS LTD	LU	19.1%	0.07%
23	317955945	Excavation	2009	C	TENARIS CONNECTIONS LTD	LU	19.1%	0.07%
24	317744053	Excavation	2010	C	TENARIS CONNECTIONS LTD	LU	19.1%	0.07%
25	332283326	Excavation	2010	C	TENARIS CONNECTIONS LTD	LU	19.1%	0.07%
26	330387347	Excavation	2010	C	TENARIS CONNECTIONS LTD	LU	19.1%	0.07%
27	334495602	Excavation	2010	C	TENARIS CONNECTIONS LTD	LU	19.1%	0.07%
28	365035843	Excavation	2011	I	HEDRICK MARCELLE H	US	3.3%	<0.01%
29	419462931	Exploration-Drilling	2012	C	**HALLIBURTON**	US	12%	0.64%
30	442648574	Exploration-Drilling	2012	C	**HALLIBURTON**	US	12%	0.64%
31	415002460	Excavation	2013	/	/	CA		
32	422239400	Excavation	2013	C	BAOSHAN AJRON EHND STIL KO LTD	CN	3.3%	<0.01%
33	419415631	Exploration-Drilling	2013	C	**HALLIBURTON**	US	12%	0.64%
34	419449457	Exploration-Drilling	2015	C	**HALLIBURTON**	US	12%	0.64%

*C = company; I = individual.
Note: companies that are also among the top 27 innovators in mining technologies at the global level (table 1) are in bold.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Table D5 – Processing sub-trajectory

Processing	**Appln_id**	**Mining technological sub-field**	**Year**	**Type of applicant***	**Company name**	**Origin (country of residence)**	**Fraction of top main path (at company level)**	**Fraction of total processing mining patents in the dataset (18,966 overall patents) at company level**
1	50273679	Flotation	1970	C	DOW CHEM CO	US	5%	<0.01%
2	50665215	Flotation	1973	I	PETROVICH VOJISLAV	US	5%	0.11%

3	52441561	Flotation	1975	C	AMERICAN CYANAMID	US	15%	0.57%
4	52467397	Flotation	1976	C	AMERICAN CYANAMID	US	15%	0.57%
5	49116796	Flotation	1981	C	BEROL KEMI AB	SE	10%	0.07%
6	52225780	Flotation	1984	C	BEROL KEMI AB	SE	10%	0.07%
7	52941753	Flotation	1985	C	AMERIKAN TSIANAMI KOMPANI FIRMA	US	5%	<0.01%
8	48459040	Flotation	1988	C	AMERICAN CYANAMID	US	15%	0.57%
9	52736696	Flotation	1991	C	INCO LTD	CA	5%	0.10%
10	46979625	Flotation	1993	C	FALCONBRIDGE LTD	CA	5%	0.10%
11	49292111	Flotation	1999	C	NEWMONT	US	10%	0.05%
12	53618307	Flotation	2004	C	NEWMONT	US	10%	0.05%
13	56821306	Crushing/grinding mineral	2008	C	BARRICK GOLD CORP	CA	10%	0.07%
14	335176736	Flotation	2010	C	BARRICK GOLD CORP	CA	10%	0.07%
15	375608846	Flotation	2012	U	KUNMING SCIENCE & TECH UNIV	CN	5%	0.64%
16	414186769	Crushing/grinding mineral	2013	R	BEIJING GENERAL RESEARCH INST OF MINE & METALLURGY	CN	5%	0.28%
17	419548300	Crushing/grinding mineral	2014	C	WUPING ZIJIN MINING CO LTD	CN	5%	<0.01%
18	425149960	Crushing/grinding mineral	2014	C	MCC NORTHERN DALIAN ENGINEERING & TECHNOLOGY CORP	CN	5%	0.07%
19	447941878	Flotation	2015	C	QUZHOU HUAYOUGU NEW MATERIAL CO LTD	CN	10%	<0.01%
20	450145985	Mining-Mining (Ore)	2015	C	QUZHOU HUAYOUGU NEW MATERIAL CO LTD	CN	10%	<0.01%

*C = company; I = individual; R = research centre; U = university.
Note: companies that are also among the top 27 innovators in mining technologies at the global level (table 1) are in bold.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Table D6 – Refining sub-trajectory

Refining	**Appln_id**	**Mining technological sub-field**	**Year**	**Type of applicant ***	**Company name**	**Origin (country of residence)**	**Fraction of top main path (at company level)**	**Fraction of total refining mining patents in the dataset (103,438 overall patents) at company level**
1	50373977	Non-ferrous	1971	C	ALUMINIUM CO OF AMERICA	US	23%	0.18%
2	51045920	Ferrous	1974	C	ALUMINIUM CO OF AMERICA	US	23%	0.18%
3	52420139	Non-ferrous	1975	C	ALUMINIUM CO OF AMERICA	US	23%	0.18%
4	53852393	Non-ferrous	1977	C	ALUMINIUM CO OF AMERICA	US	23%	0.18%
5	52343307	Non-ferrous	1984	C	KENNECOTT CORP	US	5%	0.02%
6	48884245	Ferrous	1988	C	GILLESPIE & POWERS INC	US	5%	0.01%
7	53563266	Non-ferrous	1991	I	CLAXTON RAYMOND J	US	5%	<0.01%
8	49519773	Non-ferrous	1999	I	COOPER PAUL V	US	25%	0.03%
9	53377399	Ferrous	2001	I	THUT BRUNO H	US	12%	<0.01%
10	50307447	Ferrous	2003	I	THUT BRUNO H	US	12%	<0.01%
11	53366175	Ferrous	2004	C	MOLTEN METAL EQUIPMENT INNOVATIONS LLC	US	21%	0.03%
12	49365139	Ferrous	2005	/	/	US		
13	49721470	Ferrous	2006	C	PYROTEK INC	US	5%	0.08%
14	55341705	Ferrous	2008	C	MOLTEN METAL EQUIPMENT INNOVATIONS LLC	US	21%	0.03%
15	334683231	Ferrous	2010	C	MOLTEN METAL EQUIPMENT INNOVATIONS LLC	US	21%	0.03%
16	412510887	Ferrous	2013	I	COOPER PAUL V	US	25%	0.03%
17	443388298	Ferrous	2015	I	COOPER PAUL V	US	25%	0.03%
18	449825601	Non-ferrous	2015	/	/	US		
19	446429393	Ferrous	2015	I	COOPER PAUL V	US	25%	0.03%
20	449586087	Ferrous	2015	C	MOLTEN METAL EQUIPMENT INNOVATIONS LLC	US	21%	0.03%
21	450866727	Ferrous	2015	I	COOPER PAUL V	US	25%	0.03%

*C = company; I = individual.

Note: companies that are also among the top 27 innovators in mining technologies at the global level (table 1) are in bold.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

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Table D7 – Transport sub-trajectory

Transport	**Appln_id**	**Mining technological sub-field**	**Year**	**Type of applicant***	**Company name**	**Origin (country of residence)**	**Fraction of top main path (at company level)**	**Fraction of total transport mining patents in the dataset (19,131 overall patents) at company level**
1	9982136	Control	1972	C	UNI CHARM CORP	JP	4.5%	0.72%
2	51227437	Rail	1974	C	BYURO PATENT AG FIRMA	CH	10.5%	0.03%
3	52640018	Rail	1976	C	BYURO PATENT AG FIRMA	CH	10.5%	0.03%
4	47602051	Control	1979	C	AB CARRAGO TRANSPORTSYSTEM	SE	4.5%	0.01%
5	49738336	Control	1982	I	BOULAIS RICHARD A	US	4.5%	<0.01%
6	53356025	Control	1985	C	TEXAS INSTRUMENTS INC	US	4.5%	0.10%
7	49533895	Control	1989	C	WHS ROBOTICS	US	4.5%	<0.01%
8	54372414	Control	1992	C	EATON KENWAY INC SALT LAKE CITY UTAH US	US	4.5%	0.03%
9	48750654	Control	1994	C	JERVIS B WEBB CO	US	4.5%	0.09%
10	52090676	Control	1996	C	MANNESMANN DEMATIC RAPISTAN CORP	US	4.5%	0.02%
11	45515737	Control	2001	C	FRIENDLY ROBOTICS LTD	IL	4.5%	0.05%
12	49590367	Control	2002	C	SANDIN PAUL E	US	10.5%	0.18%
13	52578675	Control	2003	C	I ROBOT CORP	US	29.5%	1.57%
14	53518173	Control	2004	C	SHARPER IMAGE CORP	US	4.5%	0.06%
15	53356233	Control	2007	C	I ROBOT CORP	US	29.5%	1.57%
16	55682683	Control	2008	C	I ROBOT CORP	US	29.5%	1.57%
17	274802936	Control	2009	C	I ROBOT CORP	US	29.5%	1.57%
18	325208193	Control	2010	C	SANDIN PAUL E	US	10.5%	0.18%

19	416435251	Control	2013	C	I ROBOT CORP	US	29.5%	1.57%
20	473681278	Control	2015	C	I ROBOT CORP	US	29.5%	1.57%
21	470166068	Control	2015	C	BOBSWEEP INC	CA	4.5%	<0.01%

*C = company; I = individual.
Note: companies that are also among the top 27 innovators in mining technologies at the global level (table 1) are in bold.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Table D8 – Automation sub-trajectory

Automation	**Appln_id**	**Mining technological sub-field**	**Year**	**Type of applicant***	**Company name**	**Origin (country of residence)**	**Fraction of top main path (at company level)**	**Fraction of total automation mining patents in the dataset (520 overall patents) at company level**
1	267925813	Automation	2009	/	/	US		
2	334521323	Automation	2010	C	TATA CONSULTANCY SERVICES LTD	IN	33.3%	0.77%
3	337040149	Automation	2011	U	CENTRAL SOUTH UNIVERSITY	CN	33.3%	1.35%
4	473581262	Refining-Non-ferrous	2015	C	CHANGTIAN INT ENGINEERING CO LTD ZHONGYE	CN	33.3%	0.77%

*C = company; U = university.
Note: companies that are also among the top 27 innovators in mining technologies at the global level (table 1) are in bold.
Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Table D9 – Blasting sub-trajectory

Blasting	**Appln_id**	**Mining technological sub-field**	**Year**	**Type of applicant***	**Company name**	**Origin (country of residence)**	**Fraction of top main path (at company level)**	**Fraction of total blasting mining patents in the dataset (3,800 overall patents) at company level**
1	52300447	Blasting	1975	C	**SCHLUMBERGER TECHNOLOGY CORP**	US	22%	4.74%
2	54013475	Blasting	1978	C	JET RESEARCH CENTER INC	US	6%	0.63%

3	48225944	Fuses	1980	C	DRESSER INDUSTRIES INC	US	6%	0.29%
4	53057070	Blasting	1985	C	**SCHLUMBERGER TECHNOLOGY CORP**	US	22%	4.74%
5	54098194	Blasting	1986	C	**HALLIBURTON**	US	22%	6.39%
6	47820965	Blasting	1987	C	**HALLIBURTON**	US	22%	6.39%
7	50849398	Blasting	1989	C	**HALLIBURTON**	US	22%	6.39%
8	47747750	Blasting	1993	C	**SCHLUMBERGER TECHNOLOGY CORP**	US	22%	4.74%
9	48761683	Blasting	1994	C	**SCHLUMBERGER TECHNOLOGY CORP**	US	22%	4.74%
10	51895775	Blasting	1995	C	**WEATHERFORD LAMB INC**	US	22%	0.71%
11	46994146	Blasting	1998	C	**HALLIBURTON**	US	22%	6.39%
12	51239438	Blasting	2000	C	**WEATHERFORD LAMB INC**	US	22%	0.71%
13	49370546	Blasting	2002	C	**WEATHERFORD LAMB INC**	US	22%	0.71%
14	46466010	Blasting	2005	C	**WEATHERFORD LAMB INC**	US	22%	0.71%
15	273717178	Blasting	2008	I	GRAY KEVIN L	US	6%	0.13%
16	339373759	Blasting	2011	C	**EXXONMOBIL UPSTREAM RESEARCH CO**	US	16%	0.68%
17	410674547	Blasting	2013	C	**EXXONMOBIL UPSTREAM RESEARCH CO**	US	16%	0.68%
18	449420352	Blasting	2015	C	**EXXONMOBIL UPSTREAM RESEARCH CO**	US	16%	0.68%

*C = company; I = individual.
Note: companies that are also among the top 27 innovators in mining technologies at the global level (table 1) are in bold.

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Appendix E Historical narrative on the evolution of the Blasting and Refining sub-trajectories over time

Evolution TMP blasting sub-trajectory	Evolution TMP refining sub-trajectory
Initially, we have three patents regarding processes, methods and apparatuses for preventing unwanted detonation of shaped charge perforating guns while in storage and in transport, yet providing quick and easy arming at the well site. Then, we have patent N. 53057070 and patent N. 54098194 that regard specific safety measures linked to, respectively, methods and apparatuses	The first five patents in the TMP of the refining sub-trajectory relate to technologies that usually treat molten aluminum, metals with an impeller. Molten aluminum is treated with selectively maintained salt flux in a compact efficient system to decrease its oxide, gas and sodium content. The system features an intensely agitated zone for contacting the metal and the salt flux followed by a quiet

for deactivating a partially flooded perforating gun assembly, and apparatuses aimed at overcoming high pressure or high temperature difficulties.

The TMP of this sub-trajectory proceeds with downhole perforating methods and apparatuses using secondary explosive detonators and perforating guns having a plurality of exploding foil or exploding bridge wire initiator apparatus responsive to a pulse of current for simultaneously detonating the plurality of charges.

Between 1995 and 1998, there are two mining patents referring to new casing opening formation apparatus which includes an explosive charge and an apparatus for positioning the explosive charge in a casing in a cased wellbore at a desired location. Patent N. 46994146 entails a method of interconnecting wellbores which is convenient and economical in its performance.

Between 2000 and 2005, we have three patented technologies used for cutting an opening through the wall of a conduit located in a borehole traversing the subsurface formations. In 2005, patent N. 46466010 contains an innovation that allows to determine the point at which a tubular is stuck with another tubular or a wellbore.

The latter four patents in the TMP (years 2008-2015) regard assembly and methods for multi-zone fracture stimulation of a well and autonomous downhole conveyance system.

separation zone. Specifically, three (patents N. 52420139, 53852393 and 52343307) out of these first five patents regard metal scrap melting system.

Then, the evolution of refining technologies changed topic between 1988 and 1999, with patented innovations concerning apparatuses for generating a vortex in a melt. In this last range of time, patent N. 48884245 represents an important invention where the vortex generator includes an impeller, which rotates within the well and actually creates the vortex. In addition, it has an elevator from which the impeller is suspended as well as a drive motor for turning the impeller, with the motor being on the elevator. An elevator frame serves to guide the elevator and the elevator frame is in turn connected to a trolley which runs along a track that passes over the charging well, but also extends well beyond it. An elevating mechanism adjusts the height of the elevator and the elevator frame with respect to the trolley and is normally set so that the impeller is immersed in the melt and the elevator frame is engaged with the furnace at the changing well as resist torque imposed by the drive motor. All the aspects illustrated ease maintenance of both the generator and well and further facilitates charging the well with scrap.

In 2001 and 2003, there are two patents that address a different issue, i.e. having impellers for molten metal pump with reduced clogging.

Between 2004 and 2010, an evolution of refining technologies linked to systems for releasing and mixing gas into molten metal has been ascertained. There is a paramount innovation in patent N. 334683231 (year 2010), which relates to a device for dispersing gas into molten metal that includes an impeller, a drive shaft having a gas transfer passage therein, a first end, a second end and a drive source. The second end of the drive shaft is connected to the impeller and the first end is connected to the drive source. The impeller includes a first portion and a second portion with a plurality of cavities. The first portion covers the second portion to help prevent gas from escaping to the surface without entering the cavities and being mixed with molten metal as the impeller rotates.

The remaining mining patents in the TMP (between 2013 and 2015) refer to molten metal transfer and degassing system through different apparatuses. For instance, patent N. 443388298 consists of a system and method for transferring molten metal from a vessel into a non-gravity assist launder*. The launder has a horizontal angle of between 0° and – 10° to help prevent dross from being pulled by gravity into downstream vessels. Another tool used to transfer molten metal from one structure to another is illustrated in patent N. 446429393. Aspects of this invention include a transfer chamber constructed inside of or next to a vessel used to retain molten metal. The transfer chamber is in fluid communication with the vessel that can enter the transfer chamber. A powered device, which may be inside of the transfer chamber, moves molten metal upward and out of the transfer chamber and preferably into a structure outside of the vessel such as another vessel or a launder.

It is worth stressing that the evolution of refining technologies in the latter period is mostly concentrated on innovations about different types of apparatuses aimed at transferring molten metal from one place to another;

	whereas technologies of the earlier period were focused on techniques regarding how to melt a metal.

*In this context, a launder is a trough for holding or conveying water, especially (in mining) one used for washing ore.

Note: These information are the outcome of an analysis carried out carefully reading titles and abstracts of the core mining patents that are in the TMP of those two sub-trajectories, listed in chronological order in tables D6 (refining) and D9 (blasting) in Appendix D.

Source: Own elaboration based on EPO-PATSTAT Database.

Appendix F Inventors' country of origin of the mining patents in the top main path of each sub-trajectory

Table F – Inventors' country of residence referring to the core mining patents in the TMP of each sub-trajectory

SUB-TRAJECTORIES	**BLASTING**	**METALLURGY**	**REFINING**	**EXPLORATION**
Geographical origin of inventors (individuals) in the TMP	100% United States	100% United States	100% United States	-91% United States -9% France
SUB-TRAJECTORIES	**ENVIRONMENTAL**	**MINING (MINE OPERATION)**	**TRANSPORT**	**PROCESSING**
Geographical origin of inventors (individuals) in the TMP	-95.5% United States -4.5% Canada	-55% United States -20% Argentina -10% United Kingdom -5% Canada -5% China -5% The Netherlands	-90% United States -10% Israel	-25% United States -75% Canada

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Appendix G Countries where the core mining patents (sub-trajectories) related knowledge diffuses

Table G – Countries where the core mining patents (TMP) related knowledge diffuses (application authority)

SUB-TRAJECTORIES	**BLASTING**	**METALLURGY**	**REFINING**	**EXPLORATION**
Countries where the core mining patents in the TMP are filed	100% United States	100% United States	100% United States	-100% United States
SUB-TRAJECTORIES	**ENVIRONMENTAL**	**MINING (MINE OPERATION)**	**TRANSPORT**	**PROCESSING**
Countries where the core mining patents in the TMP are filed	-94% United States -6% Japan	-88% United States - 6% China -3% Canada - 3% European Patent Office	-95% United States - 5% Germany	- 70% United States - 30% China

Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Chapter 4

Mining Innovation, Technological Diversification and Profitability[♦]

Abstract

This paper examines how the economic performance of firms engaged in mining innovation is affected by their portfolios of patents.

Combining WIPO data on the patenting activities of over 245,000 firms with specific reference to nine mining technologies for the period 1970-2015 with Orbis data on these firms profitability over the period 2010-2018, we find that mining companies' innovative activities have on average a negative effect on their profitability, presumably reflecting the high costs of innovation in this field and a conservative attitude of firms in most segments of the mining value chain. Innovation in blasting and metallurgy technologies makes a relevant exception to this rule, as patenting in this field appears to have a strong and significantly positive effect on firms' profits. This may relate to the nature of such technologies which are both cost-cutting and applicable in a variety of different contexts within and across the boundaries of the mining industry, hence yielding higher profits. Conversely, environmental technologies have a negative impact on profitability – at least in the relatively short term - possibly because they are more sector-specific and they compel firms to bear compliance costs due to stricter environmental regulations at the national level.

We also find that being technologically diversified in terms of innovation activities across different stages of the mining value chain negatively affects the companies' profits, potentially indicating that it is less costly (and more profitable) to develop mining innovations that are related to the firms' core technological competencies.

Keywords

Mining innovation; Mining GVCs; Patents; Profitability; Technological diversification

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4.1 Introduction

Profitability is the primary goal of all business ventures. Without profitability, the business will not survive in the long term, with managers constantly looking for ways to change the business to improve profitability (Hofstrand, 2006).

In the mining industry in particular, the most viable strategy to make profits is to invest in prospectively low-cost operations and keep costs under rigid control throughout the mining life cycle. For the sake of completeness, even commodity cycles and price spikes can affect profits. Cost cutting should be a permanent discipline if companies are to survive under the harsh regime of weakening market prices (Crowson, 2001).

Determinants of profitability include a variety of financial, structural, strategic and efficiency factors (Bogliacino and Pianta, 2013; Burja, 2011), most of which are beyond the scope of this paper. Innovation and technological change are among the acknowledged drivers of profitability, and this can be expected to apply also to the mining industry (Humphreys, 2019; Tilton, 2014), and are the focus of this paper.

In this paper, we examine the impact of mining innovation on the profitability of a large sample of companies that have filed at least one mining patent between 1970 and 2015. Following analyses conducted in different contexts by Dosi, Grazzi and Moschella (2017), Patel and Pavitt (1995) and Pugliese et al. (2019), among others, we consider these companies' portfolio of mining patents[69] as a proxy for their technological competencies and innovation activities in mining.

While looking at the complex relationship between innovation and firm performance, several studies identified that such a relationship could be specific to some categories of firms, or conditional upon a combination of firm characteristics Coad, Mathew and Pugliese, 2020; Mathew and Paily, 2020).

In effect, each firm owns different technological competencies that are firm specific, cumulative and emerge from the various learning processes the firm has passed through. These internal competencies, together with specific behavioural patterns, enable the firm to better face changes in the market in order to survive or even to obtain profits over time (Cefis and Ciccarelli, 2005; Malerba and Orsenigo, 1995). A related stream of literature investigates the relationship between technological diversification and the economic performance of firms (i.e. profitability) (Palepu, 1985). Technology diversification is defined as the corporation's expansion of its technological competence into a broader range of technological areas (Granstrand and Oskarsson, 1994). Technological diversification may lead to increased profits in several ways. For instance, there may exist static economies of scale to the extent that the same (general-purpose[70]) technologies can have wide applicability in many different product areas with only minor adaption costs (Bresnahan and Trajtenberg, 1995; Conti, Gambardella and Novelli, 2019). Another example relates to different technologies having the potential to cross-fertilize other technologies, producing new functionalities and increased product/process performance when combined. This cross-

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[69] This cumulated number of mining patents is considered as a stock variable and it mainly captures the stock of knowledge and competencies that the firm has cumulated between 1970 and 2015 in our case.

[70] Market structures, and particularly the vertical relationships between suppliers and buyers, have important implications for the efficiency with which innovations are generated. In this respect, an important insight is that in some markets the production of GPTs (General-Purpose Technologies) can have profound implications for the vertical division of innovative labour, thus for overall economic efficiency and profitability (Conti, Gambardella and Novelli, 2019; Rosenberg, 1982). This also applies to the mining industry, which is characterised by a large portion of innovation carried out by suppliers to mining enterprises (Molina, Olivari and Pietrobelli, 2016; Scott-Kemmis, 2013).

fertilization then yields what can be called true economies of scope, providing better economic returns for the company (Granstrand and Oskarsson, 1994). Nonetheless, technological diversification can often negatively affect firms' profits when it regards too different technology fields (or technology sub-fields within a technology field) one from another (Pugliese et al., 2019). In fact, the existing evidence on the relationship between technological diversification and firm economic performance has shown that, instead of "total[71]" technological diversification, coherent technological diversification usually has a positive impact on firm performance (e.g. profits) because it basically is cheaper (see e.g. Piscitello, 2004; Pugliese et al., 2019). When the different technology fields (or technology sub-fields) share a similar underlying knowledge base, a firm's technology portfolio is considered as technologically coherent (Leten, Belderbos and Van Looy, 2007).

The extant literature has found that the relationship between innovation, technological diversification and profitability is differentiated and varies across sectors (Klepper, 1997) and firms (Teece, 1986). In the specific sectoral domain of mining, there has been a historical debate on whether the latter is indeed an innovative industry or not (see chapter 3 of this thesis). Iizuka, Pietrobelli and Vargas (2019) and Sanchez and Hartlieb (2020) argue that it is often perceived as a conservative sector, where innovation takes only a secondary role. The overwhelming characteristic of the industry is continuity and its progress is prosaic (Humphreys, 2016).

Nevertheless, many argue that mining is more likely to be comparable with high-tech industries, considering that it utilizes vanguard technologies in its processes, e.g. automated or remote-controlled machineries and advanced monitoring systems for the collection and analysis of large amounts of data (Bartos, 2007).

Most mining technologies are not developed in-house by mining companies but are rather provided by suppliers of mining firms, i.e. METS (Mining Equipment Technology Services firms) (see e.g., Andersen and Noailly, 2019; Calzada Olvera and Iizuka, 2020; Humphreys, 2019). According to the Pavitt Taxonomy of Innovation (Pavitt, 1984), the mining sector would thus be largely characterised as involving supplier-dominant innovations. Firms in predominantly traditional manufacturing industries are typically placed in this category in the original taxonomy. In the analysis below, we include METS firms alongside other mining firms.

We do expect a weak (or negative) impact of mining innovation on profitability for the following reasons.

Firstly, the goal of a supplier-dominant innovator is cost-cutting because users of their products are price sensitive. Considering that mineral commodities provide little scope for product differentiation and that profits are generated from the difference between the market price and production costs, innovation in mining is mainly aimed at cost-reduction of mining operations (Calzada Olvera and Iizuka, 2020; Iizuka, Pietrobelli and Vargas, 2019). Relatedly, there are limits to cost reductions and therefore the profit effect of mining innovation. When such innovation is successful in reducing costs, it may positively affect companies' profits. Daly, Valacchi and Raffo (2019) add that profits in the mining industry are largely affected by booms and busts in mineral-commodity prices. Secondly, innovation in mining is not likely to generate increased demand (Calzada Olvera and Iizuka, 2020), potentially hampering profits. Thirdly,

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[71] Total technological diversification is the sum of random technological diversification (across many and unrelated technology fields) and coherent technological diversification (across few and related technology fields). In this paper, for the sake of brevity, we refer to total technological diversification using the term technological diversification.

the knowledge upon which this type of innovation is based has a low level of appropriability (Calzada Olvera, 2021). 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 innovation (Calzada Olvera and Iizuka, 2020).

Considering the dynamics of innovation in the mining industry, it is necessary to consider the different industries which comprise the mining industry and that are carried out along a value chain (Calzada Olvera, 2021). In fact, in recent decades, mining companies have increasingly organised their activities along Global Value Chains (GVCs) (Iizuka, Pietrobelli and Vargas, 2019; Pietrobelli, Marin and Olivari, 2018), a phenomenon that may involve stronger linkages among firms and with other actors. This paper considers the impact of mining innovation on profitability taking into account a GVC perspective. After finding that mining innovation as a whole negatively influences profits, we disentangle the heterogeneity of innovations within the mining sector, assuming that different mining technologies along the mining GVC may have a different impact on the companies' profitability. More precisely, we divide the total portfolio of mining patents of the firms innovating in mining technologies into 9 sub-portfolios, i.e. mining technological fields in the WIPO Mining Database. These nine sub-portfolios (i.e. blasting, exploration, mine operation, processing, metallurgy, refining, automation, environmental and transport technologies) of mining patents represent different stages along the mining GVC, with a different potential impact on the corporate's profits. Instead of confirming whether it is more profitable to innovate in upstream or downstream stages along the mining value chain, we find that mining technologies that have a general-purpose[72] feature (being applicable across multiple domains beyond mining) and are particularly aimed at reducing costs positively influence corporate's profits. This is true in the case of blasting (upper-middle phase along the mining GVC) and metallurgy (downstream stage on the mining GVC) technologies, for example. Conversely, environmental innovations related to mining activities negatively affect firms' profits, possibly reflecting their sector-specificity (Aron and Molina, 2020) and the fact that companies are compelled to invest in these type of innovations because of stricter environmental regulations (Andersen and Noailly, 2019).

As a final step, we move beyond the heterogeneous impact of different technology sub-portfolios within mining, computing an index of technological diversification in terms of the nine heterogeneous mining innovations representing different stages along the mining GVC. Specifically, we test to what extent being technologically diversified (Gambardella and Torrisi, 1998; Leten, Belderbos and Van Looy, 2007) influences firms' profitability. In this context, we find that being technologically diversified in terms of innovation activities across different stages of the mining value chain negatively affects firms' profits. This might reveal that it is less costly (and more profitable) to develop mining innovations that are related to the firms' core technological competencies (Pugliese et al., 2019).

Moreover, this negative impact of technological diversification on profitability also reflects the nature of innovation in the mining industry, which is of an incremental nature (Calzada Olvera and Iizuka, 2020; Pietrobelli, Marin and Olivari, 2018). Incremental innovations do not necessarily require technological diversification, because they generally entail small improvements to existing technologies within the same mining sub-industry.

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[72] Such novel mining technologies are producing operational changes across the value chain and their use is not necessarily exclusive for a specific activity (Sanchez and Hartlieb, 2020).

The remainder of the paper is structured as follows. Section 2 discusses existing literature as a means of illustrating and developing the paper's research questions. Section 3 describes the data utilized and the characteristics of the mining industry using descriptive statistics. Section 4 illustrates our econometric model. Section 5 shows and discusses the results. Section 6 concludes with ideas for future research.

4.2 Background literature and research questions

Studies on the relationship between innovation and profits are often predicated on a view of profit seeking as the motivation behind investment in innovation and technology, both in industry models (Klepper, 1997), in studies of firms (Cefis and Ciccarelli, 2005; Teece, 1986) and in analyses that address industry models and studies of firms in an integrated way (Bogliacino and Pianta, 2013).

Cefis and Ciccarelli (2005) argue that answering this question (i.e. the impact of innovation on profits) sheds light not only on the different patterns of innovation, but also on the understanding of industrial dynamics. In their analysis, Cefis and Ciccarelli (2005) found that innovations have a positive effect on profits after controlling for relevant characteristics at both the sector and firm level. Their results also suggest that innovating firms maintain their profit differential as time goes by. Nonetheless, they also stressed that non-innovating firms could develop competencies and capabilities (other than those required for innovating) that enable them to earn profits which are as high as those of innovators. Nonetheless, it is worth stressing that the requirement to invest in sunk costs, which are independent of the returns to innovation, and to fund product development and market diffusion activities (which some estimates place at 10-20 times the initial R&D costs) may be such that there is an inevitable negative impact on retained profits.

Part of the extant literature finds a negative relationship between innovation and profits (see e.g. Cerulli et al, 2021; Grabowski et al., 2002; Hanel and St-Pierre, 2002). For instance, Cerulli et al. (2021) find a negative relationship between patents and firm profits because of additional investments (costs) associated to patenting activity that are captured by the denominators of the profitability indices (Grabowski et al., 2002).

It is worth noting that the effect of innovation on profitability also depends on the firm's capacity to appropriate the benefits from innovation. Appropriability varies from industry to industry and depends on the effectiveness of instruments of intellectual property protection and strategies used by firm to prevent competitors to imitate their innovations (Hanel and St-Pierre, 2002). In the specific case of the mining industry, innovations are characterised by a low level of appropriability, thus potentially hindering firms' profits (Calzada Olvera, 2021).

As a first step, we study the impact of overall mining innovation on firm profitability.

Especially in the mining industry, the most viable strategy to make profits is to invest solely in prospectively low-cost operations and keep costs under rigid control throughout the mining life cycle. Cost cutting has to be a permanent discipline if companies are to survive under the harsh regime of weakening market prices (Crowson, 2001). It is worth stressing that, in general, innovation in the mining industry has cost-cutting purposes (Iizuka, Pietrobelli and Vargas, 2019).

Humphreys (2019) and Tilton (2014) pinned down the drivers that shape changes of economic performance and profitability in mining. They are, among others: resource depletion and ore quality, government regulations, worker quality, innovation and technological change, economies of scale, investment lags, capacity utilisation, strikes and other unplanned production stoppages and other factors such as management, organisation and market structure.

We can notice that innovation is only one among many drivers of economic performance, which is measured in terms of profitability in our case. Nevertheless, for several reasons, we decided to focus on mining innovation as a factor that may potentially affect the profits of our sample of companies that patents in mining technologies. From an industry perspective, innovation is necessary to tackle the fundamental challenges encountered by mining operations worldwide, e.g. 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. From a development perspective, innovation is necessary for extending linkages to convert the sector from being the "enclave" (Calzada Olvera and Iizuka, 2020).

The capital-intensive feature of mining implies large investments upfront. Iizuka, Pietrobelli and Vargas (2019) state that the large-scale investment is usually followed by large-scale operations whose profits tend to rely on economies of scale. This large scale and long time span of operation contribute to risk averse and conservative technology choices[73]. The life cycle of mines (typically 20 to 30 years) further slows technological change as the change must coincide with the mine's investment cycle. The mining companies' time lag in taking up new technologies has been estimated as 13 years on average (Barnett and Lopez, 2012). Thus, technological innovation in this sector has many restrictions due to the way business functions and this makes trickier for technological innovation to be profitable.

As a second step, we dig deeper into the relationship between mining innovation and profitability examining the effect of innovation carried out at different stages along the mining GVC on the firms' profits. It is highly important to distinguish between mining technologies from a GVC perspective, considering that very different mining innovations from each other shape the mining GVC, and thus they might have different impacts on profitability.

Calzada Olvera and Iizuka (2020) state that the mining industry 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. Involvement in GVCs can offer opportunities for the suppliers of mining firms to innovate (Iizuka, Pietrobelli and Vargas, 2019; Pietrobelli, Marin and Olivari, 2018). In the mining sector, a new context is emerging, which is opening new opportunities for innovation and fruitful linkages between lead firms and METS (suppliers to mining companies), which did not exist before (Perez, 2010; Marin et al., 2015). These new opportunities are associated with a larger and more diversified demand for natural resources, new knowledge and technology advances applicable to these sectors, outsourcing along GVCs[74], together with the search for local technological solutions and an increasing pressure to innovate to reduce environmental impact (Iizuka and Katz, 2015). Nevertheless, value chains with the typical characteristics of mining GVCs may have governance structures that might to some degree generate a market failure for innovation (Molina, Olivari and Pietrobelli, 2016). This is

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[73] The enormous financial, environmental and social consequences of some innovative device or process not working as expected, or failing to work at all, are significant deterrents to adoption (Dunbar et al., 2016).

[74] Though large global suppliers are important actors for the development of new technologies, the outsourcing tendency has also opened the opportunity for the emergence of local knowledge intensive mining suppliers (Stubrin, 2017).

particularly true in emerging countries where the local and national innovation system could not provide the underlying knowledge base for the suppliers to "upgrade" into the possible technological opportunities (Iizuka, Pietrobelli and Vargas, 2019).

In recent years, the industry has focused relentlessly on short-term profitability, i.e. the financial performance over a couple of years (Deloitte, 2017), exacerbating this behaviour with respect to innovation and contributing to subpar productivity levels. For instance, the mining firms' procurement decision is largely controlled by the headquarters and tends to adopt incremental and ad hoc, proven technological solutions from established local suppliers (Atienza, Lufin and Soto, 2018). Nonetheless, the link between innovation and profitability in the mining industry should not be decoupled. Mining firms increase the linkage with suppliers (backward linkages) when mineral prices decline to carry out cost-reducing innovation (e.g. customization, the introduction of digital technologies) and to maximise profits (Calzada Olvera and Iizuka, 2020). Consequently, suppliers' innovative efforts become larger than that of mining firms and it augments counter-cyclical to commodity prices.

Innovation can take place on different stages along the mining GVC (Torres Mazzi, 2018). Briefly describing the mining value chain from upstream to downstream stages, it is worth pointing out that the exploration stage includes activities such as ore body discovery, mineral determination, resource estimation and feasibility studies. The mining operation stage includes activities such as mine planning, design and development, mine construction, extraction of ore bodies and mineral processing. Once the mineral has been processed, then refining can occur. Each stage of the process is supported by services, e.g. transport, waste treatment and energy generation (Daly, Valacchi and Raffo, 2019). We do expect the effect of innovation on profitability to differ at different points in the mining value chain.

To have a well-defined depiction of how innovation takes place along the mining GVC and its link to profitability, it is extremely important to take into account not only mining companies, but also METS companies, as we did in this paper with mining patent data matched with firm-level data. Different innovations' cost-cutting abilities (Pietrobelli, Marin and Olivari, 2018) and the fact that some of these technologies along the mining GVC may be general-purpose technologies[75] (Conti, Gambardella and Novelli, 2019), with a wider range of applicability to several or many sectors of the economy (potentially more profitable), beyond mining, can lead these different impacts on economic performance.

Innovation in all these phases is mainly driven by cost-cutting purposes that are also aimed, consequently, at improving profitability (Iizuka, Pietrobelli and Vargas, 2019). Moreover, the integration of different areas of related knowledge is useful to improve and upgrade existing tools and machinery. For example, the mining supplier company Exsa in Peru, combining knowledge about engineering, explosives, new materials and chemistry developed a new method of rock fragmentation called "Quantex" that generates savings of up to 20% of total costs and has positive environmental impact. The technology has been patented in Peru and the US (Aron and Molina, 2020; Molina, Olivari and Pietrobelli, 2016). This seems to suggest that blasting technologies (mostly used in middle value chain activities, e.g. to extract the minerals) are particularly keen to reduce costs and therefore improve profits. Another example relates to

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[75] Rosenberg (1982; p. 71) suggested that as the economy becomes increasingly characterized by the presence of specialized general-purpose technologies suppliers and higher rates of general-purpose technologies purchases from downstream buyers in other industries, not taking these buyer-supplier relationship fully into account is a fundamental limitation of most of the literature on technological innovation. We averted this problem taking into account the suppliers of mining companies, i.e. METS firms in our analysis on the impact of mining innovation on profitability.

the Chilean METS High Service that obtained three patents concerning remote monitoring and wireless communication which allows predicting wear points for key equipment; in this way it is possible to anticipate replacements and avoid to stop operations, which can cost about USD 150 thousand per hour (Iizuka, Pietrobelli and Vargas, 2019).

As a last step, we empirically examine the relationship between technological diversification and economic performance (see e.g. Palepu, 1985; Pugliese et al., 2019) of the firms active in mining innovation.

We build on previous literature related to the wealth of theoretical contributions spurred by the widespread interest in understanding the determinants of corporate product diversification (e.g. Montgomery, 1994; Teece et al., 1994). A great deal of empirical work has also been devoted to understanding the relation between the performance of firms and the number of activities or markets in which they engage (Miller, 2004; Palich et al., 2000). However, products are not the only area in which companies diversify and it has not escaped scholarly attention that the drivers of corporate technological scope are a meaningful area of investigation. This line of inquiry has gained prominence especially in the last decades of the twentieth century (Pugliese et al., 2019). Specifically, firm learning dynamics has been represented through the process of consolidation/expansion of firms' technological competencies. Such a process has also been called input or technological diversification (Piscitello, 2004). Technological competencies have been defined by Bell and Pavitt (1993) as the resources needed to generate and manage technological change, including skills, knowledge and linkages.

It is worth adding that Dosi and Teece (1993) have distinguished organisational-economic competencies[76] from technological competencies of companies (fundamental to identify technological diversification), and have argued that the latter derives from the former, and is therefore more fundamental to the firm. Nonetheless, Patel and Pavitt (1995) argue that a firm's accumulated technological competence strongly constraints the directions in which it searches. The differentiated nature of technological competencies is one of the most important factors explaining the coherence and the boundaries of the firm (Malerba and Marengo, 1995).

Moreover, Pavitt (1998) states that most of the times technological diversification anticipates product and market diversification. This is so because technological exploration in a wide range of technologies is a prerequisite for production (Breschi, Lissoni and Malerba, 2003).

These are among the reasons why we chose to detect the level of technological diversification of our sample of companies that patent in mining technologies, and to see how this impacts on their financial performance. For the sake of completeness, technology diversification at the corporate level means an increase in the diversity, or the breadth of the corporation's technology base. For example, it can be a mechanical engineering corporation that recruits electronics engineers in order to develop electronic control equipment in its product and/or production process, or a chemical engineering corporation adding biology competence to its R&D team. Such an expansion does not necessarily have to be concomitant with product diversification (Granstrand and Oskarsson, 1994). Palepu (1985) emphasizes

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[76] Organisational-economic competencies involve: allocative competencies regarding the decision of what to produce and how to price it; transactional competencies, i.e. deciding whether to make or buy; administrative competencies on how to design organisational structures and policies to enable efficient performance (Dosi and Teece, 1993).

that the more diversity a firm has in its operations and/or technologies, the better are its chances of extracting higher profits.

After all, whether companies focus or diversify is relatively uninteresting unless one can link these patterns to economic performance (Gambardella and Torrisi, 1998). The arguments in the industrial organization literature linking diversification to profitability (one measure of economic performance) revolve around the notion of market power (Markham, 1973). Because of its ability to acquire and exercise market power, a technologically diversified firm is alleged to be able to subvert competitive market forces through mechanisms such as cross-subsidization, predatory pricing, reciprocity in selling and buying and barriers to entry. Another mechanism that is expected to allow diversified firms to sustain supernormal profits is the "information loss" that arises from the ability of a diversified firm to conceal the profitability of its individual business segment (Palepu, 1985). These arguments lead to the thought that the more diversity a firm has in its technological competencies, the better are its chances of extracting profits (Piscitello, 2004). However, it does not always happens that technological diversification has a positive impact on economic performance (Dosi, Mathew and Pugliese, 2020). In effect, a difficulty for (randomly[77]) technologically diversified firms could be that they deal with numerous activities, based on differentiated technologies and too heterogeneous research projects. This can be quite expensive for the firm (Nesta and Saviotti, 2005; Pugliese et al., 2019). Furthermore, when a firm operates in a set of "related" technologies, it is possible for it to exploit its "core factors" leading to economies of scale and scope, efficiency in resource allocation and opportunity to exploit particular technical and managerial skills (Kim, Lim and Park, 2009; Palepu, 1985; Rumelt, 1982).

Given the above discussion, we pose the following research question:

RQ1: How do mining innovation activities of firms that patent in mining technologies affect their profitability?

We apply this line of arguments to the companies innovating in mining technologies at the global level, testing if their inventive activities in mining affect their economic performance, measured in terms of profitability (see, among others, Bogliacino and Pianta, 2013; Dosi, Mathew and Pugliese, 2020; Gambardella and Torrisi, 1998; Mathew and Paily, 2020; Palepu, 1985).

We use the companies' portfolio of mining patents as a proxy for detecting the mining innovative activities and technological competencies of the firms following Dosi, Grazzi and Moschella (2017), Patel and Pavitt (1995) and Pugliese et al. (2019) among others.

RQ2: How do firms' mining innovation activities carried out on different stages along the mining value chain influence their profitability?

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[77] In their econometric analysis, Pugliese et al. (2019) found that the number of connected technologies within the technological knowledge portfolio of their sample of companies, as quantified by their measure of coherence, is more relevant to economic performance than the raw number of technological fields in which the company innovates.

Considering that we were able to split the total portfolio of mining patents of the companies patenting in mining technologies into nine "sub-portfolios[78]", representing different stages along the mining value chain, we develop the following research question.

To the best of our knowledge, the impact of innovation carried out along the MGVC stages on profitability has not been previously studied for the mining industry.

RQ3: How does technological diversification within mining technologies affect the profitability of the firms active in mining innovation?

More precisely, we measure the level of technological diversification (of the applicant companies) taking into account patents of the nine mining technological fields or "sub-portfolios" (WIPO Mining Database) above mentioned.

4.3 Data

4.3.1 The dataset

We aim to investigate the relation between the structures of the mining technological portfolios of firms and their economic performance, which we measure with profitability. To extract this last information, we rely on ORBIS, a commercial database maintained by Bureau van Dijk Electronic Publishing (BvD), which specializes in providing financial, administrative and balance sheet information about companies based worldwide. The database accounts for over 20 million companies for which public data is collected and harmonized sourced from several providers using a multitude of data typically collected by public institutions.

A notable advantage of ORBIS is its connection with the WIPO Mining Database, which collects information on patents related to mining technologies[79] from all over the world over the period 1970-2015. Each mining patent has an application identifier (appln_id) which corresponds to the application identifier in EPO-PATSTAT. Joining the two databases (ORBIS and WIPO) leaves us with detailed information about 246,051 applicant firms that filed at least one mining patent over the period 1970-2015, and for which firm characteristics and balance sheet information are available between 2010 and 2018.

We consider the mining patent portfolio of these companies (a total of 520,687 mining patents) between 1970 and 2015 as a stock, a time-invariant variable. It is a proxy for their technological competencies and backgrounds (Dosi, Grazzi and Moschella, 2017; Patel and Pavitt, 1995; Pugliese et al., 2019)

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[78] The nine "sub-portfolios", i.e. mining technological fields in the WIPO Mining Database are exploration, blasting, mining (mine operation), processing, metallurgy, refining, transport, automation and environmental.

[79] The dataset refers to technologies concerning metallic and non-metallic minerals, and coal.

As Batterham (2004) explains, in the mining industry, capital is a large component of the costs and so, once having invested, it is difficult to justify changes within a period of 5-30 years. The cycle times between knowledge generation (which comes at a cost) and implementation of the innovation (the return on that cost) are often much longer than the typical 1–2-year lag between capital expenditure and cash flows. For instance, in Australia, there is a huge lag, on average 13 years, between the release of a technology and its adoption within coal operations (Barnett and Lopez, 2012). This is another reason why we decided to use the number of mining patent applications per each company as a time-invariant variable (It is also a way to consider them as a lagged variable). Especially in the case of mining technologies, it is tricky to exactly fix the economic returns and the impact on profitability of patented innovations over time.

In the WIPO Mining Database, mining technologies are divided into 9 technological classes: exploration, blasting, mining (mine operation), processing, metallurgy, refining, transport, automation and environmental. Those technological fields are carefully selected on the basis of a patent search strategy[80] based on a combination of International Patent Classification (IPC) codes and keywords in PATSTAT (for details referring the patent search strategy, the description of each mining technological field and further information see Daly, Valacchi and Raffo, 2019). These nine technological classes stand for different stages along the mining value chain. The lifecycle of mining, from discovery of an ore body to extraction of minerals and finally to returning the land to its natural state consists of several distinct steps that are summarized in the figure in appendix A.

4.3.2 Characteristics of the firms patenting in mining technologies

This section illustrates the characteristics of our sample of firms using WIPO and Orbis data.

Scott-Kemmis (2013) argues that, due in large part to slowing growth and profitability, mining innovation became more incremental and more dependent on suppliers in the last quarter of the 20th century. The structure of the mining industry was transformed by a wave of mergers and acquisitions at the global level. Some companies became part of multinationals. One important trajectory of change has been the search for lower costs through increasing the scale and durability (and hence longevity) of mining, transport and crushing equipment.

The mining industry is no longer a vertically integrated activity where all of its phases and corresponding activities take place within the boundaries of a multinational enterprise (Scott-Kemmis, 2013). A series of changes in corporate strategies, the emergence of digital transformations and other new technologies, among other factors, have led to a de-verticalization of the mining industry. "The world looks at mining as one industry, but it is a collection of industries with different supply and demand dynamics" (Deloitte, 2017; p. 1). Hence, the dynamics for innovation are better understood by looking at the different industries which comprise the mining industry, and that are carried out along a value chain (Calzada Olvera, 2021; Pietrobelli, Marin and Olivari, 2018). Figure 1 provides descriptive evidence on this, revealing that a non-negligible number of non-mining firms also carries out innovation in the mining sector. It is worth pointing out that in this analysis, as in chapters 2 and 3, we consider the mining industry

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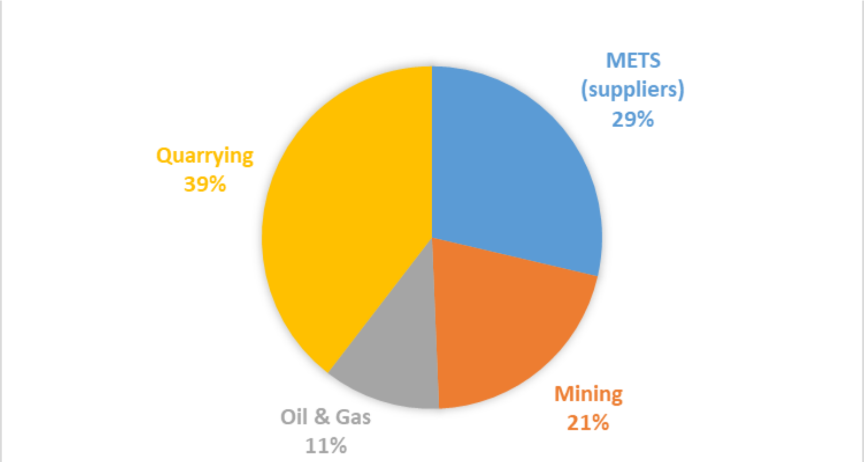
[80] The definitions of the 9 mining technological fields are based on the mine lifecycle and supply chain (see Daly, Valacchi and Raffo (2019; pp. 7-8)) and stages in the mineral extraction process.

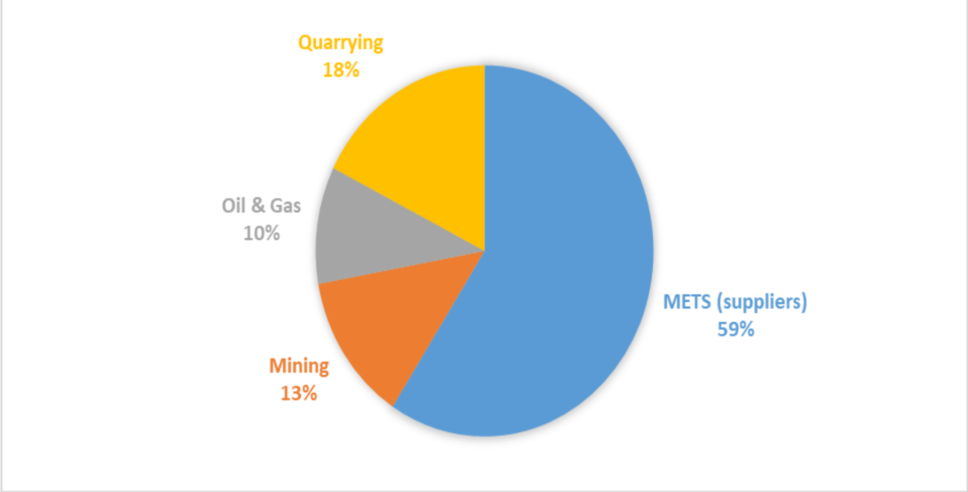
as a collection of firms that innovate in mining technologies (not only those that produce mineral commodities) and may belong to other industries, different from mining.

Figure 1

a) Economic sector to which the companies patenting in mining technologies belong



b) Share of mining patents invented by type of company[81]



Note: the distinction among METS, mining, oil & gas and quarrying firms is a taxonomy present in the WIPO Mining Dataset and it is based on NACE Rev. 2 industry classifications. More generally, mining, oil & gas and quarrying companies belong to the extractive sector.

Source: Own elaboration on WIPO Mining Database and BVD Orbis.

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[81] For the sake of correctness, percentages in this pie chart cannot correspond to the similar pie chart in chapter 2. The reason is related to the fact that, in this context, we have the applicant companies coming from Bureau Van Dijk data source. In the same pie chart in chapter 2, there are all the applicant companies, including those coming from national data sources different from Bureau van Dijk. However, it must be said that the vast majority of applicant firms contained in the WIPO Mining Database were taken into account to retrieve related balance sheet information from ORBIS database. We have a large sample of firms, i.e. 246,051.

Figure 1a depicts that 21% of the companies innovating in mining technologies are mining companies in the strict sense (producers of metallic and non-metallic minerals). 11% of the total sample are oil & gas companies and 39% are quarrying firms, even though they can be considered more generally under the extractive industry as the mining companies.

Nearly one third (29%) of the companies patenting in mining technologies are suppliers to mining companies, i.e. METS (Mining Equipment Technology Services) firms. The METS mostly belong to the manufacturing sector (see appendix B for their NACE Rev. 2 correspondence table). It is in figure 1b that we can get aware of the essential role of the METS companies in mining innovation. In effect, 59% of the mining patents owned by our sample of companies is invented by mining suppliers, revealing that they perform better from an innovative viewpoint than the other companies from the extractive sector.

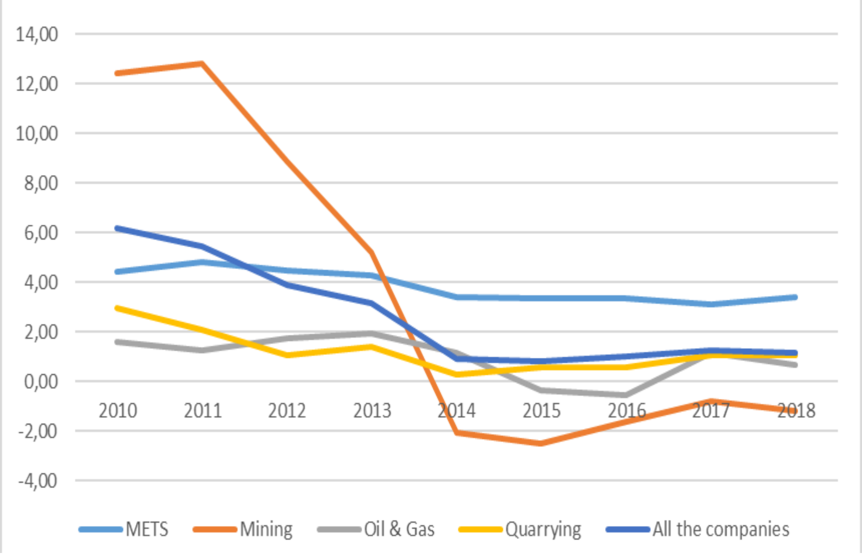
Bartos (2007) and Humphreys (2019), among others, point out that many of the ground-breaking technologies being developed in mining are not the products of the mining industry itself, but of the METS sector. Moreover, besides technological learning processes, knowledge-intensive suppliers have been key for turning natural resource industries into knowledge-based industries with high innovation capabilities. Knowledge intensive suppliers, from equipment to engineering services, have also been fundamental for the competitiveness of the industry itself, and the emergence of knowledge intensive clusters (Urzua, 2013). It is essential not to forget that innovation in the mining sector often faces some restrictions due to the physical infrastructure of the mine (e.g. scale of architecture, width of corridors, layout and technological level of equipment installed and so on) designed at the start of the mine's life cycle, that can set certain limits to how many changes can be introduced at a later stage (Iizuka, Pietrobelli and Vargas, 2019).

The increasing reliance of the mining sector on outsourcing and the specialisation of mining suppliers have been widely observed in the past two decades (Scott-Kemmis, 2013). This was further augmented by the increase in foreign direct investment, market liberalisation and the advancement of technology that lowered logistic costs (Calzada Olvera and Iizuka, 2020).

It is possible to state that outsourcing has become a major corporate trend in the mining sector as it is associated to a reduction in cost operations, productivity growth and increased profitability (Zhu, Hsu and Lillie, 2011). It ranges from non-core activities (e.g. cleaning and security services) to core mining activities, from drilling, blasting, equipment performance checking to warehousing (Peterson, LaTourrette and Bartis, 2001).

Considering that, in this paper, we are interested in the effect of mining innovation on economic performance, i.e. profitability, we show the trend over time of the profitability ratio called ROA (return on assets) related to the firms patenting in mining technologies.

Figure 2 – ROA (%) over time of the firms patenting in mining technologies, 2010-2018



Note: ROA = (Operating Income (EBIT)/Total Assets) x 100

Source: Own elaboration on BVD ORBIS dataset.

Figure 2 portrays that all the companies considered together (dark blue line) had a slightly downward trend in profitability, especially between 2010 and 2013.

The METS companies are the best performers on average; the only exception is between 2010 and 2013, when mining firms showed a higher ROA than the other firms, even though in sharp decline. After the year 2013, mining firms showed a negative ROA. A very similar trend is confirmed using a different profitability ratio, i.e. ROE (return on equity) (see appendix C on this).

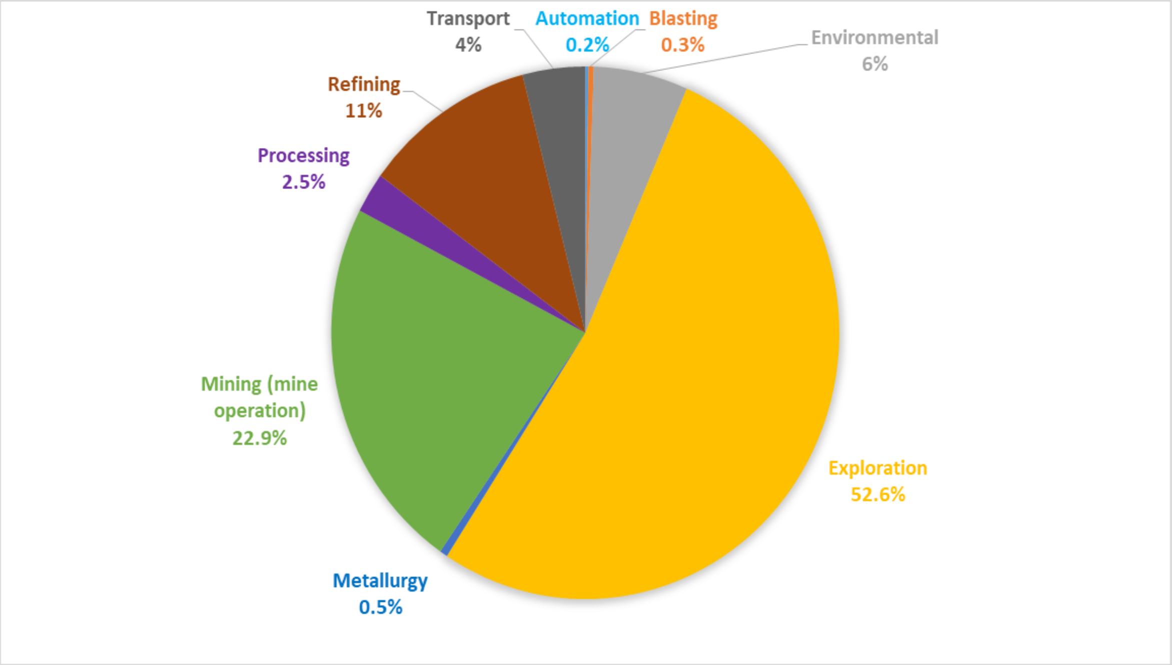
The recurring poor profitability of mining firms may lay on the supply side of the mining industry, with the producers themselves (Crowson, 2001).

The industry's tendency to move away from high-risk enterprises (e.g. exploration) and bringing new mining technologies to the market is rooted in the pro-cyclicality of the industry and the pressure to maintain profitable margins (Calzada Olvera, 2018). Filippou and King (2011) argue that the low profitability in the mining industry has been caused by the long run price decline in commodities which in turn has been attributed to the downward price-cost spiral, i.e. cost reduction measures during low price times and the industry's inability to raise prices back. This price-cost spiral has become even more tricky to counterweight as the industry is now relentlessly focused on delivering short-term profitability, which severely undermines corporate investment and deters growth (Deloitte, 2017).

We need to remember that the price of mineral commodities is exogenous and firms have no control over the price. This implies that the only means left for a firm to change revenue (and thereby profits) are: increasing the volume of production without increasing costs; increasing the efficiency of mineral deposits by finding more productive deposits; reducing the cost of production to a minimum by reducing fixed costs[82]. This means that innovation should ultimately be aimed at these three objectives (Calzada Olvera and Iizuka, 2020).

In order to properly consider the impact of mining innovation and technological diversification on firms' profitability, we need to dig deeper into different types of innovations in mining, interpreted from a global value chain perspective (Daly, Valacchi and Raffo, 2019; Pietrobelli, Marin and Olivari, 2018). In practice, we divide the total portfolio of mining patents of each company into nine "sub-portfolios" of mining patents (representing different stages along the MGVC), corresponding to the nine mining technological fields in the WIPO Mining Database. The following figure 3 represents the patenting activities of all the firms in the ORBIS Dataset.

Figure 3 – Share of mining patents owned by the companies per each mining technological field, 1970-2015



Note: see figure A in appendix A to be aware of the positioning of each of the nine mining technologies along the mining value chain.

Source: Own elaboration on WIPO Mining Database and BVD ORBIS.

In figure 3, it is possible to notice that more than 90% of global mining innovation (carried out by applicants that are companies) is concentrated into four mining technological fields, i.e. exploration (52.6%), mining (mine operation) (22.9%), refining (11%) and environmental (6%). The remaining

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[82] A large portion of the mining industry's costs is fixed. One possible way of lowering unit costs is to spread the fixed element across a larger output (Crowson, 2001).

companies' inventive activities in mining technologies are focused on transport (4%), processing (2.5%), metallurgy (0.5%), blasting (0.3%) and automation (0.2%).

It is not surprising that exploration technologies represent more than a half of global mining innovation because they are "key technologies" for the mining industry (e.g. Calzada Olvera and Iizuka, 2020; see also chapter 2 for a thorough discussion on this). Exploration is an upstream stage along the MGVC and it is the process of finding and exploration of the mineral deposit (Daly, Valacchi and Raffo, 2019). It is a high-risk and uncertain phase; in addition, exploration and discovery have to become more efficient and the technology used to detect and characterize mineral deposits on and below the earth's surface must become more capable. Vast amounts of money are being spent on exploration (Albanese and McGagh, 2011). Given this reasoning, it cannot be excluded that having patents in exploration technologies may not affect (or negatively affect) firms' profitability.

The distinction of mining patents into different mining technological fields, representing different stages along the mining value chain is crucial to answer our RQ2 (impact of mining innovations developed referring to different phases along the MGVC on profitability) and RQ3 (impact of companies' technological diversification in terms of these nine mining technological fields on profitability).

4.4 Empirical strategy

Our approach to consider the relationship between innovation and firm-level profitability follows a similar approach to Coad, Mathew and Pugliese (2020), Dosi, Mathew and Pugliese (2020) and Piscitello (2004), who adopt a panel fixed effects regression model of the form:

$$\begin{aligned} ROA_{it} = \alpha + \beta_1 inno_{i,t} + \beta_2 innoGVC_{i,t} + \beta_3 inverseHerf_{i,t} + \beta_5 \ln ta_{i,t} + \beta_6 \ln fa_{i,t} \\ + \beta_6 solvrat_{i,t} + \omega + \sigma + \gamma + \varepsilon_{it} \end{aligned}$$

Following the bulk of studies on the diversification-profitability linkage (see Palich et al., 2000 for a survey on this), we use an accounting measure of profitability as the dependent variable, namely the return on assets (ROA), which is widely used in the literature (see e.g. Cerulli et al., 2021; Dunbar et al., 2016; Miller et al., 2013; Narware, 2010; Khidmat and Rehman, 2014; Kim et al., 2004; Piscitello, 2004). ROA is considered an accounting-based indicator and superior to other profitability ratios such as ROE[83] (Return on Equity), which may be affected by capital structure as well as operational efficiency (Kim et al., 2004). The variable is defined as:

$$ROA = \frac{\text{Operating income (EBIT}^{84}\text{)}}{\text{Total assets}}$$

---

[83] However, we use ROE (Net income/Shareholders funds) as alternative dependent variable (Cerulli et al., 2021; Han et al., 1998; Khidmat and Rehman, 2014; Palepu, 1985; Zabri et al., 2016) replicating the same econometric model, in order to have a well-defined robustness check following Palepu (1985).

[84] EBIT is Earnings Before Interests and Taxes.

While there is a possible reverse causality problem between innovation and profitability, with profits being a crucial source of funding for innovation activities, patents filed in year *t* are the results of past innovation efforts rather than investments in the same year of the application.

Our main explanatory variables of interest are:

(i) The cumulative number of mining patents ($inno$) over the period 1970-2015, which is our measure of mining technological competencies/capabilities of each company in our dataset (see e.g. Breschi et al., 2003; Granstrand and Oskarsson, 1994; Patel and Pavitt, 1995; Pugliese et al., 2019). Given that the patent variable is firm-specific (and it does not vary over time), it is not possible to include firm fixed-effects in our analysis.

(ii) A set of nine variables capturing the split of the cumulative number of patents into the nine technological fields in which companies can carry out patenting activities in the mining sector and which are defined above (i.e. $innoGVC_j$, where j is the technological field and patfield refers to the cumulative number of patents over the period 1970-2015 in that patent field).

$$ROA_{it} = \alpha + \sum_{j=1}^{9} \delta_j \, innoGVC_{i,t} + \beta_3 inverseHerf_{i,t} + \beta_5 \ln ta_{i,t} + \beta_6 \ln fa_{i,t} + \beta_6 solvrat_{i,t} + \omega + \sigma + \gamma + \varepsilon_{it}$$

(iii) An inverse Herfindahl index as an indicator of the level of technological diversification (Dosi, Grazzi and Moschella, 2017; Dosi, Mathew and Pugliese, 2020). In particular, our index of technology diversification is defined as (1 – H), where H is Herfindahl's concentration index[85] (Gambardella and Torrisi, 1998; Ganstrand and Oskarsson, 1994; Leten, Belderbos and Van Looy, 2007; Piscitello, 2004) applied to the mining patents classified into the nine mining technological fields present in the WIPO Mining Database in each company. The Herfindahl is calculated as:

$$H_i = \sum_{j=1}^{9} \left(n_{ij}/N_i\right)^2$$

Where n_{ij} is the number of mining patents of technology field j in company i, and N_i is the total number of mining patents in company i.

We also include the following set of control variables in the analysis:

- The log of firm size as defined by the total assets of the firms ($\ln ta$) following Piscitello (2004) and Pugliese et al. (2019)

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[85] We decided to normalize the inverse of the Herfindahl index (Cracau and Lima, 2016) in the following manner:

$$H_{inverse} = \frac{\left(H - \frac{1}{N}\right)}{1 - \left(\frac{1}{N}\right)}$$

Where: H is the inverse Herfindahl index; N = 9 (in our case) is the number of mining technological fields. The normalized Herfindahl indicator takes on values between 0 and 1.

- The log of fixed assets ($\ln fa$) (Agiomirgianakis et al., 2006; Ietto-Gillies, 2020). We decided to control for fixed assets because, on the balance sheet of most mining companies, the value of fixed assets such as property, plant, equipment and mineral concessions is between 60% and 70% of the value of total assets (Dunbar et al., 2016). In the case of METS (supplier) companies, that are mostly equipment manufacturers, the level of fixed assets may be high as well, considered that they need to keep costly tangible fixed assets (e.g. machineries) to produce equipment for the mining firms[86].
- The solvency ratio ($solvrat$) following Khidmat and Rheman (2014). The solvency ratio (asset based) is computed as the ratio between shareholders funds and total asset.

ω, σ and γ refer to a set of time, country of firm origin and industry[87] fixed-effects.

4.5 Results and discussion

Table 1 shows summary statistics of all the variables included in our fixed effects model.

Table 1 – Summary statistics

VARIABLES	**MEAN**	**STANDARD DEVIATION**	**MIN**	**MAX**
ROA	0.0361	0.1908	-1	1
Log of total assets	7.4667	2.4595	-6.8734	19.3307
Log of fixed assets	6.1188	3.0396	-11.2664	19.3028
Solvency ratio	0.4304	0.3733	-1	1
Total portfolio of mining patents	6.6519	123.9991	1	14174
Portfolio of **blasting** mining patents	0.0302	1.8064	0	326
Portfolio of **environmental** mining patents	0.5156	8.9569	0	526
Portfolio of **exploration** mining patents	2.3239	67.3571	0	11652
Portfolio of **metallurgy** mining patents	0.0444	1.0005	0	101
Portfolio of **mining (mine operation)** mining patents	2.1488	44.3306	0	3560
Portfolio of **processing** mining patents	0.2265	4.5476	0	243
Portfolio of **refining** mining patents	0.9571	23.0161	0	2134
Portfolio of **transport** mining patents	0.3863	9.3184	0	1032

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[86] It is worth remembering that the major part of the companies in our sample are suppliers (METS) to mining companies.

[87] Industry fixed effects regard the four macro-sectors to which our sample of firms belongs, i.e. METS, mining, quarrying and oil & gas.

Inverse of the normalized Herfindahl index	0.0142	0.0963	0	0.9262

Source: Own elaboration based on BVD ORBIS and WIPO Mining Database.

Table 2 reports the results from our econometric analysis of the effect of innovation on firm profitability. The results in this table rely on firm level data over the period 2010-2018 and use the return on assets as our dependent variable. In robustness analysis, we further use an alternative measure of profitability (return on equity) (see Table D2 in Appendix D) and report results using a cross-section of data for 2012 rather than the time-varying data (see Table D1 in Appendix D). This latter robustness test acknowledges the fact that our main explanatory variables do not vary over time. We will further discuss the results of these robustness tests in the text.

Table 2 – Impact of mining innovation and technological diversification on profitability: fixed effects model (time span 2010-2018)

DEPENDENT VARIABLE: RETURN ON ASSETS (ROA)					
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Log of total assets	0.0116*** (0.0004)	0.01172*** (0.0004)	0.01183*** (0.0004)	0.01188*** (0.0004)	0.0119*** (0.0004)
Log of fixed assets	-0.0069*** (0.0003)	-0.0069*** (0.0003)	-0.0069*** (0.0003)	-0.0069*** (0.0003)	-0.0069*** (0.0003)
Solvency ratio (Shareholders funds/total assets)	0.1311*** (0.0014)	0.1311*** (0.0014)	0.1312*** (0.0014)	0.1312*** (0.0014)	0.1312*** (0.0014)
Total portfolio of mining patents	-0.00002** (1.00E-05)			-1.4E-05* (7.65E-06)	
Portfolio of **automation** mining patents		-0.0021 (0.0018)			-0.0022 (0.0015)
Portfolio of **blasting** mining patents		0.0017* (0.0010)			0.0018* (0.0010)
Portfolio of **environmental** mining patents		-0.0003*** (0.0001)			-0.0002* (0.0001)
Portfolio of **exploration** mining patents		-0.00003 (0.00002)			-0.00004 (0.00003)
Portfolio of **metallurgy** mining patents		0.0011* (0.0006)			0.0012** (0.0006)
Portfolio of **mining (mine operation)** mining patents		-0.00001 (0.00001)			-0.00001 (0.00001)

Portfolio of **processing** mining patents		-0.00004 (0.0001)			0.00005 (0.0001)
Portfolio of **refining** mining patents		0.00001 (0.00002)			-0.00001 (0.00002)
Portfolio of **transport** mining patents		-0.00001 (0.00003)			-9.26E-07 (0.00002)
Inverse of the Herfindahl index (in terms of the 9 mining tech fields)			-0.0440*** (0.0048)	-0.0384*** (0.0056)	-0.0330*** (0.0053)
Constant	-0.0296 (0.0747)	-0.0303 (0.0747)	-0.0313 (0.0746)	-0.0316 (0.0746)	-0.0317 (0.0746)
Time fixed effects	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Sector fixed effects	Yes	Yes	Yes	Yes	Yes
No. of observations	317,247	317,247	317,247	317,247	317,247
R^2	0.1671	0.1674	0.1674	0.1674	0.1676

Standard errors clustered by firm in parenthesis.

* $p<0.1$, ** $p<0.05$, *** $p<0.01$

Note: Automation + blasting + environmental + exploration + metallurgy + mining (mine operation) + processing + refining + transport "sub-portfolios" of mining patents = Total portfolio of mining patents.

Source: Own elaboration based on BVD ORBIS and WIPO Mining Database.

If we begin by looking at the coefficient on the patent indicator, we observe a coefficient that is negative and significant, suggesting that those firms that have undertaken the most patenting activity over the period 1970-2015 tend to have lower profits, all else equal.

Such as result is partially consistent with the view that innovation, apart from through its importance for cost cutting is not a main priority for mining companies and it is not among the main drivers of their profitability (Batterham, 2013; Ernst & Young, 2010). Moreover, improving profitability through increasing scale and incremental innovation has delivered fewer returns over time to investment in innovation (Scott-Kemmis, 2013).

Calzada Olvera and Iizuka (2020) state that the goal of a supplier-dominant innovator is cost cutting because users of their products are price sensitive. Furthermore, the knowledge upon which mining 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.

While it would be wrong to dismiss the importance of technology to mining and metallurgy, transformative technologies are rare and some of those that appear to offer transformations, such as high-pressure acid leach (HPAL) for nickel, do not work out as intended. This reveals that, in some cases, the investments and the money spent in mining innovation may not have an economic return, hindering overall profits. Humphreys (2016) argues that there are good reasons for this. Physical laws govern the recovery and extraction of metals. These do not change with time and metal processing accordingly offers limited scope for the application of breakthrough technologies, in contrast to what happens in many other sectors of the economy (Bartos, 2007; Tilton, 2003).

The capital intensity of the industry also encourages conservative behaviour. There might be a problem of assets irreversibility. When laying out a lot of money, it may make sense to go with a conventional process that is tried and tested rather than a new one which looks better on paper but which might prove very costly indeed if it does not work as intended. As a number of companies have found to their cost, scaling up from the lab to a commercial scale plant can be hazardous (Humphreys, 2016). It may not raise sales or prices given the nature of mining and the physical conditions can limit cost reduction effects of (what is costly) innovation.

Moreover, in the context of our analysis, the negative sign of the portfolio of mining patents' coefficient may also be due to the negative sign of environmental technologies (in models 2 and 5 in Table 2).

Splitting mining innovation activities into the nine different innovation stages along the mining value chain, we find important differences across the different mining technological fields.

We find for example that patenting in blasting (upstream/middle stage along the mining value chain) and metallurgy (downstream phase along the mining value chain) technologies are positively and significantly related to profitability (models 2 and 5 in Table 2).

One reason for these positive effects may relate to the fact that these mining innovations are more general-purpose technologies[88] and have a broader application in many sectors of the economy (beyond the mining sector) than others, which are sector-specific. Gambardella and McGahan (2010) state that the innovating firms can increase their overall profits by expanding the number of applications to which their technology can be applied. The generality of their technology may also mean that the innovator is less constrained to be oriented toward a single, co-specialized licensee as a potential downstream partner, and therefore less dependent on the success of any specific partner. At the same time, the downstream licensee is compelled to complete development for its own commercial purposes by adapting the general technology into an application that is specifically relevant to its customer set, thus incurring development costs that might otherwise be incurred by the general-purpose innovator (Bresnahan and Trajtenberg, 1995; Conti, Gambardella and Novelli, 2019).

Figure 4 reports information on which economic sector the companies that invented at least one mining patent in each of the nine mining technological fields in the dataset belong to.

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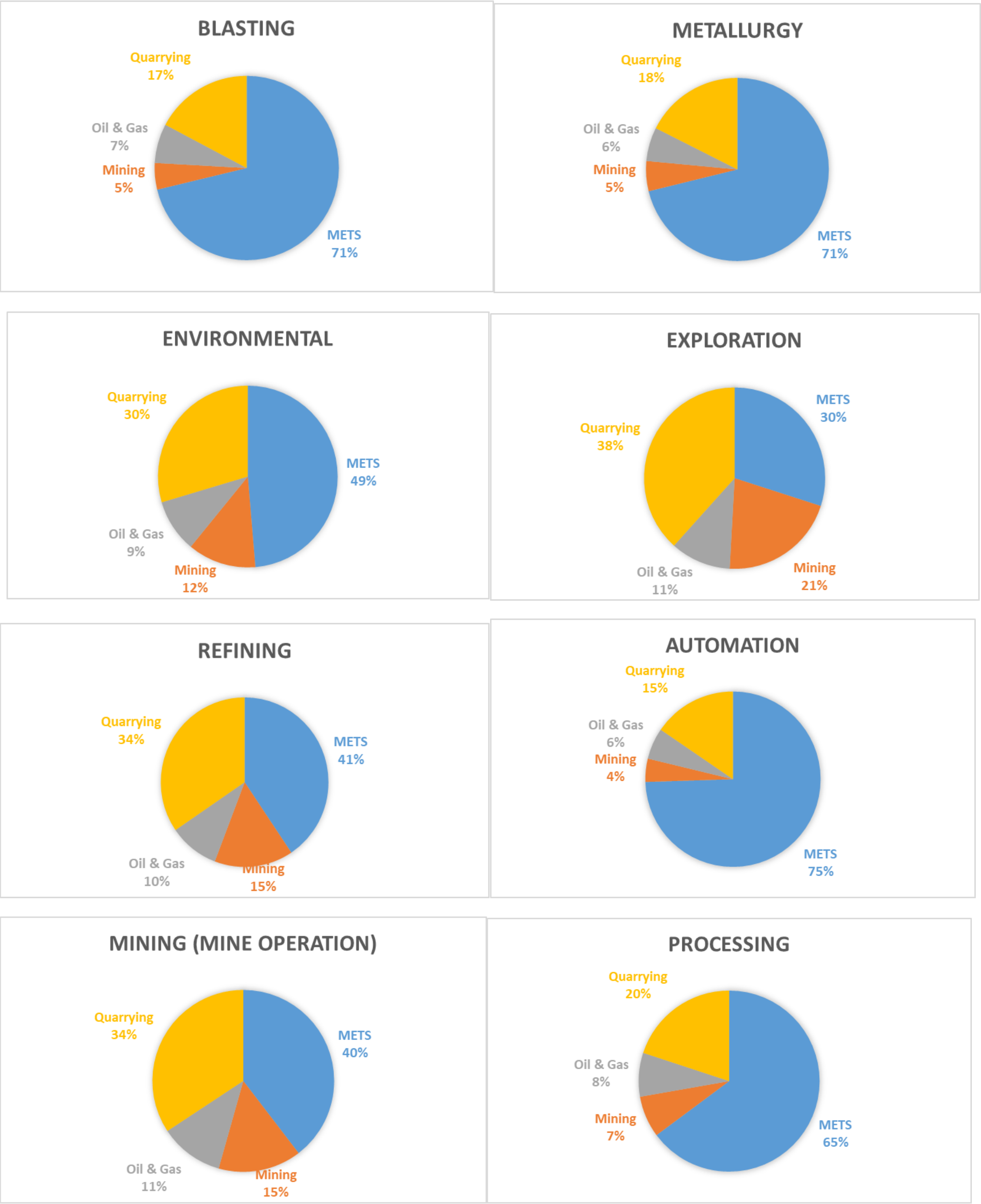
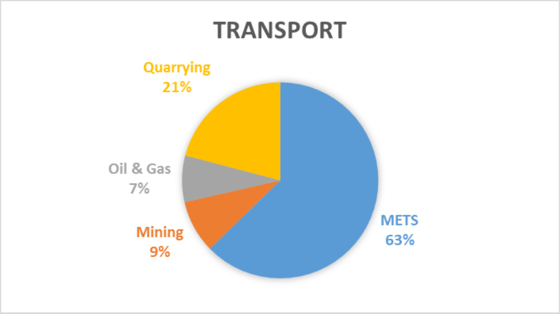
[88] We refer to Rosenberg's (1982) definition of general-purpose technologies characterised by their broad applicability in many markets as engines of economic growth and profitability for firms.

Figure 4 – Economic sectors to which the applicant companies that invented at least one mining patent in each mining technological field belong





Note: the distinction among METS, mining, oil & gas and quarrying firms is a taxonomy present in the WIPO Mining Dataset and it is based on NACE Rev. 2 industry classifications. More generally, mining, oil & gas and quarrying companies belong to the extractive sector.

Source: Own elaboration based on BVD ORBIS and WIPO Mining Database.

Figure 4 reveals that 71% of the applicant companies that invented mining patents in blasting and metallurgy are non-mining firms, i.e. METS that belong to the manufacturing and the service sector. Blasting and metallurgy are the mining technological fields with the highest share of METS (after automation)[89]. In other words, METS dominate in most fields, but they are more dominant in blasting and metallurgy.

Another further reason why blasting and metallurgy technologies have a positive and significant effect on profitability is that these two technologies are particularly aimed at reducing costs (Seccatore, 2019; Singh, 2000; Zhang, 2014a).

As portrayed in table A in appendix A, blasting technologies can be used in upstream and middle stages along the mining value chain; they are used in the exploration phase, but mainly to extract the minerals and to cope with production issues (Daly, Valacchi and Raffo, 2019).

Rock blasting[90] has a great potential to make mining processes more profitable by limiting costs (Seccatore, 2019). The factors influencing the mineral loss in mining process can be many such as the mining method, the mining plan, the drilling plan and techniques, the blast plan and operation, the loading operation and the cut-off control in production and so on (Zhang, 2014b). Among these, rock blasting is considered one of the most important factors (Zhang, 2014a).

Albanese and McCaugh (2011) argue that fragmentation in hard-rock surface mines is almost entirely dependent on explosive rock breakage, and this is unlikely to change in the near future. In terms of effectiveness and cost, blasting provides the ability to liberate large quantities of material to a size that can be moved using standard excavation and transport equipment. Given that blasting lies at the core of the mining process chain, it is not surprising that considerable research has gone into explosive formulation, initiation techniques and simulation (Batterham and Bearman, 2005). This fact is also

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[89] Even processing and transport patents have METS as prevalent applicant companies (65% and 63% respectively), but with slightly lower percentages than blasting and metallurgy.

[90] Rock mass characteristics play a major role in all aspects of blast performance. Explosive energy level and explosive distribution must be matched to geological conditions in order for a blast to be successful. Initiation and timing sequence must be compatible with the rock mass response to explosive loading. The blasting engineer cannot make these adjustments without adequate information and understanding of the rock mass characteristics (Singh, 2000). The blasting of the rock involves the interaction between the detonation products of an explosive and the confining rock mass. It is important to identify the rock mass properties that influence blasting performance and to modify blast designs to suit different rock mass conditions.

confirmed in chapter 3, where the sub-trajectory "Blasting" is the less "technology bounded" sub-trajectory, together with "Refining", in comparison to the other seven sub-trajectories. The knowledge of fragmentation and muckpile formation that can be yielded by this approach will enable blasting to be better matched to downstream requirements. This is part of the move toward an optimized mining process, free of disruptions from poor blast performance.

Rock blasting is the first phase of comminution, completed by mechanical means downstream in the crushing and milling phases (Cardu et al, 2012). Specifically, rock blasting reduces the rock from the infinite size of the half-space (Boussinessq, 1885) to a transportable size. With comminution being a cascade process, and blasting being the most upstream process, it has everything to offer to facilitate the downstream operations of mechanical comminution (Seccatore, 2019). Among the comminution costs, Paterson (2000) found that very large increases in blasting costs only slightly affect the overall operational costs. In fact, the mechanical comminution has a specific cost by orders of magnitude higher than the comminution by means of explosives, meaning that increasing blast costs always benefits the overall costs of operation.

Sophisticated blasting techniques that provoke very fine fragmentations can not only increase the mineral recovery in mining process but also reduce the energy consumption in the down-stream operations such as crushing and grinding. In addition, a very fine fragmentation can also make extraction speed increased (Zhang, 2008), meaning that mining productivity will be increased and/or mining costs decreased. Thus, it can be for example that sophisticated blasting techniques can have an impact on the cost of more downstream processes along the mining GVC.

While the results on blasting and metallurgy suggest a positive effect on profitability, the coefficient on environmental innovation has a negative and significant coefficient indicating that environmental innovation related to mining activities is associated with lower firm profitability. This is also confirmed in our robustness analysis in Appendix D.

It needs to be highlighted that, in the case of green innovations, financial barriers can be more predominant than in other types of innovation (Aron and Molina, 2020). The barriers are the long period for investment payback (Berrone et al., 2013) and the higher perceived risk for potential investors when compared to generic innovations (Kapoor and Oksnes, 2011). Linking this back to the discussion on general-purpose technologies, Aron and Molina (2020; p. 359) found that green innovations in the mining sector are of a highly specialized nature. Their sector-specificity is also confirmed in figure 4, where environmental technologies are invented by a definitely lower share of non-mining firms (METS) than blasting and metallurgy innovations.

From an empirical standpoint, Hojnik and Ruzzier (2016) confirm through a case study investigation that the initial investment to implement an eco-innovation is the most predominant internal barrier for innovative firms. Thus, it is very costly to carry out green innovations and this might negatively influence firms' profitability.

Clean technologies are characterized by a "double externality". First, just like all technologies, green technologies generate knowledge spillovers (the knowledge externality) and second, they contribute to reducing the negative externality of pollution (the environmental externality). Due to this dual market failure, firms have little incentives to invest in clean innovations in the absence of government intervention and public policies are always justified to encourage the development of these technologies

(Jaffe, Newell and Stavins, 2005). Andersen and Noailly (2019) found evidence that stringent environmental policies are associated with higher levels of green patenting activities in the mining sector.

However, Hilson (2002) argues that environmental policy may bring benefits even to the firms if it leads to the implementation of cost-saving technologies or new profitable production processes. Although adopting environmental innovations may lead to productivity gains, the literature is inconclusive on whether this will be sufficient to offset compliance costs[91].

The only other mining technological field that reports a significant coefficient is metallurgy, with the coefficient being positive and significant.

This sector is a downstream stage along the mining GVC that involves chemical treatment of minerals to produce commercial pure metals. The technologies included under this heading include smelting, electrometallurgy, pyrometallurgy and methods and apparatus (Daly, Valacchi and Raffo, 2019).

The development of electrometallurgical methods of smelting is one of the most important advances, both in electrical and metallurgical science. It allows for an increase in efficiency, reduced costs of production and a positive environmental impact (Campbell, 1912; Kinnunen and Kaksonen, 2019). The special cost-cutting nature of these specific innovations may be one of the reasons it positively influences firms' profits.

Concerning electrometallurgy, Robinson (2016) argues that operating and capital cost reduction is the driving force behind technology development in the electrolytic process field. Reducing energy and labour costs are central to overall cost reduction. Large-scale electrolytic refining of copper, nickel and lead has focused on economic performance improvements including electrode handling automation to reduce costs, whereas the higher energy consuming copper electrowinning has developed energy reduction technology. To sum up, considering that some metallurgy technologies are strongly linked to reducing corporate costs, it is expected that they positively impact on profits.

We turn, finally, to the issue of whether technological diversification has an impact upon profitability. The results indicate that being technologically diversified in terms of the nine mining technological fields present in the data has a significant and negative impact on the firms' profits. The coefficient on the inverse Herfindahl index is always significant and negative. The results thus suggest that diversification in many different mining technological fields – and at different points along the value chain – can impact negatively upon firms profits.

This finding is also linked to the nature of innovation in the mining industry. During the history of the mining industry, there have been innovations which dramatically increased productivity and reduced costs; examples include open pit mining, block caving, sulphide flotation and metal leaching (Bryant, 2015). In recent decades, however, most of innovations in mining consist of improving existing

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[91] Experts also consider that a key driver in the adoption of green innovations in the mining industry is the role they play in contributing to overcoming social conflicts that are associated with the environment. In fact, there is no doubt that these conflicts inflict enormous costs on mining firms (Aron and Molina, 2020).

technologies, without major breakthroughs (Calzada Olvera, 2021). This is linked to the above discussion on related technological diversification.

In the past, global mining firms had large R&D groups, but attention switched to developing a portfolio of projects closely aligned to the core business in the 1990s. In other words, productivity gains have come through small incremental improvements applied step-wise over many years to existing processes. They have come from new equipment that is simply a bit better than the old equipment. It has come from small improvements in work practices. It is a matter of chipping away, of sweating the small stuff, of marginal gains and attention to detail (Humphreys, 2016). Most in-house R&D groups will focus on technological solutions to specific issues, typically of an incremental nature (Bartos, 2007). It is worth stressing that if companies carry out incremental innovations on existing technologies, they might not need to be technologically diversified at all. In other words, within mining there are fewer synergies in different types of innovation, which can raise costs of innovation, without providing large benefits.

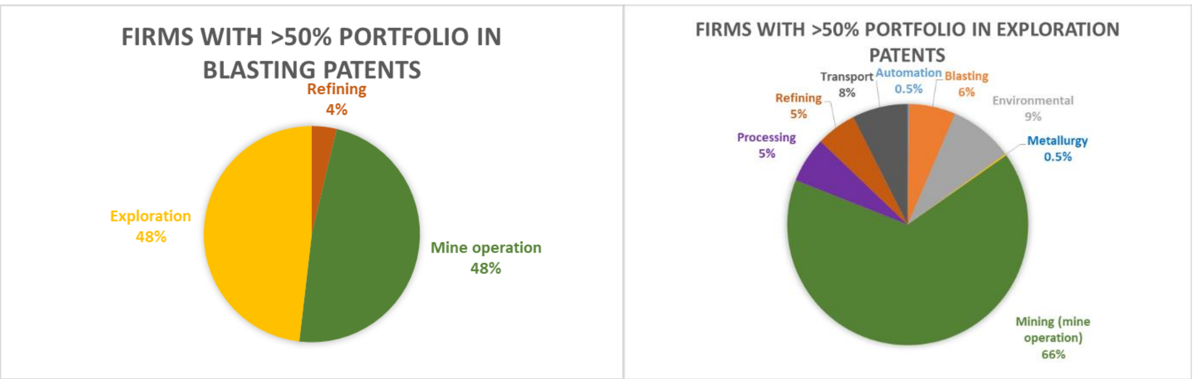
Nevertheless, it is worthwhile to point out that the concept of coherent technological diversification is different from that of incremental innovations, which are intended within a single mining technological field.

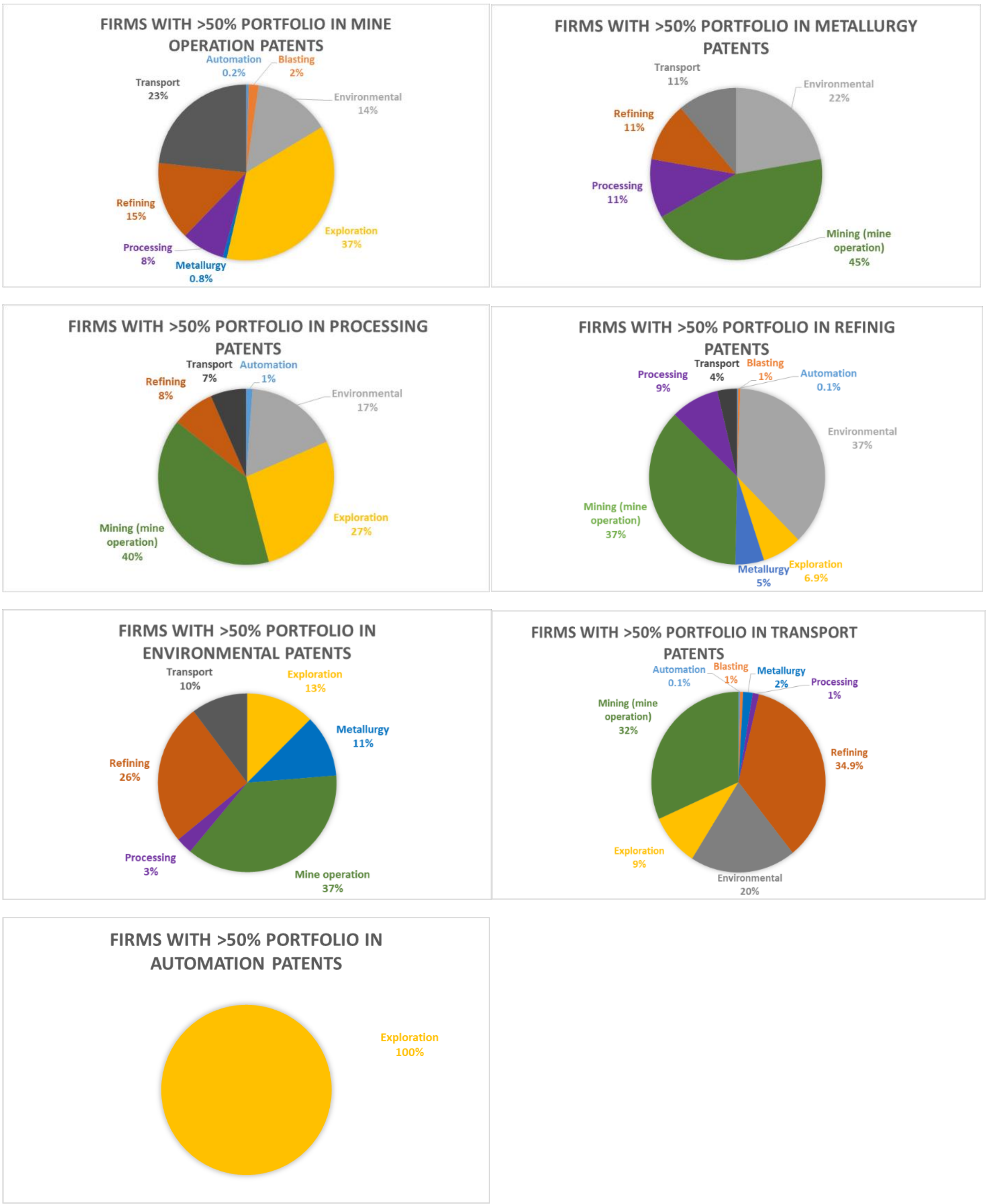
In this view, it is intuitively appealing to think that innovators' efforts to diversify their knowledge base should focus on adding domains that are functionally adjacent to their current knowledge stock rather than on taking blind leaps through the technology space (Pugliese et al., 2019).

In order to check in a preliminary way if the companies patenting in mining technologies are coherently technologically diversified, we proceed as follows. We fix the core mining technological field in which the firms specialize, with a portfolio of mining patents greater than 50% in that specific field. Then, we show the other (remaining) mining technological fields into which the firms have a patenting activity, doing this for each of the nine mining technological fields. We consider some mining technological fields as "related", the ones referring to innovations related to a close positioning along the mining value chain, following extant literature (see Appendix A on this).

Figure 5 portrays this in regards to the nine mining technological fields.

Figure 5 – Patenting activities of the firms in different mining technological fields, given and exceeding their core mining technological field (i.e. >50% of their mining patents in that core field)





Source: Own elaboration based on BVD ORBIS and WIPO Mining Database.

Figure 5 depicts that coherence may well be a relevant possibility in mining. The companies that have a core technological competence in blasting, for example, have a higher patenting activity in mining (mine operation) and exploration technologies. In addition, the companies that are specialized in mine operation and exploration have, respectively, relevant shares in exploration and blasting, and in mine operation and blasting. These three mining technological fields share related technologies and their position is in upstream-middle stages on the mining GVC (Albanese and McGagh, 2011; Daly, Valacchi and Raffo, 2019).

The firms that are specialized in mineral processing have a greater patenting activity in mining (mine operation), which is the phase immediately before mineral processing on the mining GVC (see Figure A in Appendix A).

Environmental technologies may relate to all phases along the mining GVC, but they particularly entail middle-downstream stages of the mining value chain (Albanese and McGagh, 2011; Calzada Olvera, 2018). This is in line with our descriptive evidence, considering that refining, metallurgy, processing and mine operation show the highest shares of green innovations in comparison to the firms having a specialization in other core mining technological fields. In addition, 77% of the patenting activities of the companies specialized in environmental technologies are in middle-downstream stages along the mining GVC, namely mine operation, processing, metallurgy and refining technologies.

Briefly discussing the findings regarding the three control variables[92] (total assets, fixed assets and solvency ratio) in the regressions, we show that the greater is the firms' size (logarithm of total assets) the higher the profits are in all the five models in Table 2. This is in line with a wide range of previous literature that studies the link between firm size and economic performance (see, e.g. Dosi, Mathew and Pugliese, 2020; Piscitello, 2004; Pugliese et al., 2019).

In relation to fixed assets, we find that this control variable has always a negative and significant coefficient. It reveals that increasing the level of fixed assets negatively affects profitability. We need to remember that the value of fixed assets (e.g. mineral concessions, property, plant and equipment) is often extremely high in percentage of the value of total assets in mining firms. Dunbar et al. (2016) state that if the value of fixed assets were reduced, the result would be a significant increase in ROA, a more powerful and relatively easier approach than operating cost reduction (e.g. via innovation) or increasing capital productivity. One way to reduce the fixed assets might be through outsourcing practices. Another possible explanation of the negative sign of the fixed assets coefficient could relate to the fact that higher fixed assets also imply higher levels of amortization. Amortizations represent a cost in the companies' profit and loss account, which hinders the profits[93].

The third control variable in the regressions is the solvency ratio. It has a positive and highly significant effect on firms' ROA. The stronger the company is from a net asset point of view and the less the level of external indebtedness, the higher is its profitability (Hailegebreal, 2016; Khidmat and Rehman, 2014).

4.6 Conclusion

The objective of this paper was to study the impact of mining innovation and technological diversification on profitability of firms that patent in mining technologies.

The Schumpeterian tradition has highlighted the circular relation between market power, profitability and innovation which in turn favours further accumulation of profits. Hence, it is commonly acknowledged that innovation is among the drivers of profits, although this direction of causality may not apply to all sectors and with the same intensity. In particular, it does not seem to be one of the major drivers of

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[92] Considering that their relevance is not focal to our study, we do not provide a thorough discussion about the control variables. In fact, our focus is on the impact of innovation and technological diversification (main regressors) on profitability of the firms that patent in mining technologies.

[93] I wish to thank Dr Federica Palazzi from the University of Urbino (Italy) for this suggestion.

profitability in the mining industry (Batterham, 2013; Ernst & Young, 2010). Our econometric analysis suggests that, overall, mining innovation has a negative impact on firms' profitability. Considering that the nexus between firm's innovation and its profitability depends on appropriability conditions in which the firm operates (Hanel and St-Pierre, 2002), in the case of the mining industry, firms have a low level of appropriability (Calzada Olvera, 2021), revealing that firms have a limited capacity to appropriate the results of their innovation activities. There is an increasing perspective that having a highly connected ecosystem, with a collective approach to innovation, is fundamental in moving forward with innovation efforts beyond cutting costs to effectively increase productivity, attain better environmental performance and increase profitability (Bryant, 2015). A collaborative approach to innovation is taking place organically across the industry, but it is still incipient and usually led by the top mining companies (Calzada Olvera, 2021).

Considering that innovation activities take place differently along the mining value chain, we further considered the impact on firm profits of mining innovation carried out at nine different stages along the mining GVC. When doing this, our results indicate that patenting activities in blasting and metallurgy technologies have a positive impact on profitability. This may be because, in contrast to other mining technologies, they are general-purpose technologies, with a wider range of applicability to several or many sectors of the economy. This may make these innovations more profitable, possibly because of economies of scale and scope (Conti, Gambardella and Novelli, 2019; Gambardella and McGahan, 2010). In addition, blasting and metallurgy innovations are particularly aimed at reducing corporate costs and this benefits profitability[94].

Conversely, environmental technologies related to mining activity may negatively affect companies' profitability, at least in the short run. Firms are often considered to have few incentives to invest in green innovations considering that it is very costly (Andersen and Noailly, 2019), but they are compelled to do so by governmental policies at the national level, whose purpose is to diminish the negative environmental impact of mining activities (Iizuka, Pietrobelli and Vargas, 2019). In addition, our descriptive evidence (Figure 4) reveals that, differently from blasting and metallurgy technologies, environmental mining innovations are sector-specific in line with the qualitative findings of Aron and Molina (2020) who state that green innovations are of a highly specialized nature in the mining sector. This contributes to make them less profitable. Nonetheless, the reduction of energy and water consumption, lower emissions and waste generation are all factors that will be in the core of the "mine of the future" (Humphreys, 2019; Sanchez and Hartlieb, 2020). Companies will have to find convenient and profitable ways to develop green inventive activities. For instance, Albanese and McGagh (2011) argue that new ore-sorting and grinding techniques in the future will enable ores to be processed underground, further reducing waste movement and potentially compounding the benefits of underground processing that requires smaller, more mobile and lighter equipment. This would also be a cost-saving procedure, which may positively influence profitability. Future research could dig deeper into the effect of (mining) environmental technologies on profitability, especially since green inventions are very different one from another and can relate to all of the mining supply chain phases (Daly, Raffo and Valacchi, 2019). In practice, in the WIPO Mining Database, the mining technological field "environmental" is further disaggregated into ten mining technological sub-fields. Some of them are also

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[94] More generally, concerning mining technologies, further research could empirically disentangle the innovation effect on costs and revenues considering that profits are given by the difference between revenues and costs.

energy, time (and thereby cost) saving innovations such as waste disposal, treatment of waste water and so on. It would be interesting to consider the impact on economic performance of those ten "sub-technologies" within the environmental mining technological field.

The last step of our regression analysis was to study the impact of technological diversification across the nine different stages along the mining GVC on the profitability of our sample of companies. The results suggest that being technologically diversified in terms of the nine mining technological fields present has a significant and negative impact on the firms' profits. The results thus suggest that firms that innovate in mining technologies do not need to be active in several or many fields of mining innovation, e.g. both in upstream and downstream stages along the mining value chain at the same time. Conversely, to achieve more profitable outcomes, it would be better that they focus in one or a few mining technological fields, developing innovations that are related to their core technological competencies (Dosi, Mathew and Pugliese, 2020; Pugliese et al., 2019). A possible explanation for this might relate to the importance of sector-specific knowledge or the greater fixed costs of innovating across many fields. One reason for the negative relationship could be that more technological diversification involves less coherence in firm's technological competencies.

Similar results regarding the three research questions of this chapter are obtained in our robustness analysis, i.e.: where we use ROE (Return on Equity) as alternative dependent variable concerning the panel fixed effects regression (see Table D2 in Appendix D); where we develop a different econometric technique to estimate our profitability model, i.e. a cross-section analysis regarding year 2012 (see Table D1 in Appendix D).

Further research could address the issue of computing an indicator of "coherent" technological diversification (Dosi, Grazzi and Moschella, 2017; Pugliese et al., 2019) in mining technologies along the mining GVC, investigating its impact on firms' profits (Kim, Lim and Park, 2009). A technology portfolio is considered technologically coherent when it combines technologies that share a common knowledge base, rely upon common scientific principles or have similar heuristics of search (Breschi, Lissoni and Malerba, 2003). Companies that diversify their patent portfolio in a technologically coherent way may be able to attenuate the potential negative impact of technological diversification (Leten, Belderbos and Van Looy, 2007). In the case of the firms patenting in mining technologies, it might be that the indicator of coherent technological diversification has a positive and significant impact on their profitability.

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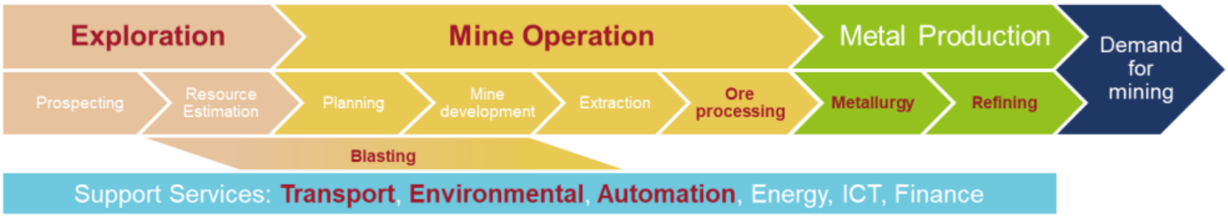
Appendix A Mining GVC stages

Figure A – Simplified view of the lifecycle of a mine



Note: The mining sub-sectors presented in red text indicate the sub-sectors defined in the patent mining taxonomy.

Source: Daly, Valacchi and Raffo (2019; p. 7).

Exploration, mining (mine operation) and blasting technologies are upper-middle stream stages on the mining value chain. Ore/mineral processing, metallurgy and refining technologies are downstream stages along the mining GVC. Transport, environmental and automation technologies represent support services to mining activities regarding the whole mining GVC (Daly, Valacchi and Raffo, 2019).

Appendix B Economic sector (NACE Rev. 2) of the METS companies

Table B – Main economic sector (Nace Rev. 2 main section classification code) to which the METS companies belong to

NACE REV. 2 CLASSIFICATION (MAIN SECTION)	% OF TOTAL METS FIRMS
A - Agriculture, forestry and fishing	0.08
B - Mining and quarrying*	7.57
C - Manufacturing	85.78
D - Electricity, gas, steam and air conditioning supply	0.03
E - Water supply; sewerage, waste management and remediation activities	0.04
F - Construction	2.91
G - Wholesale and retail trade; repair of motor vehicles and motorcycles	1.94
H - Transportation and storage	0.15
I - Accommodation and food service activities	0.06
J - Information and communication	0.10
K - Financial and insurance activities	0.17
L - Real estate activities	0.37
M - Professional, scientific and technical activities	0.48
N - Administrative and support service activities	0.24
O - Public administration and defence; compulsory social security	0.01
P - Education	0.01
Q - Human health and social work activities	0.02

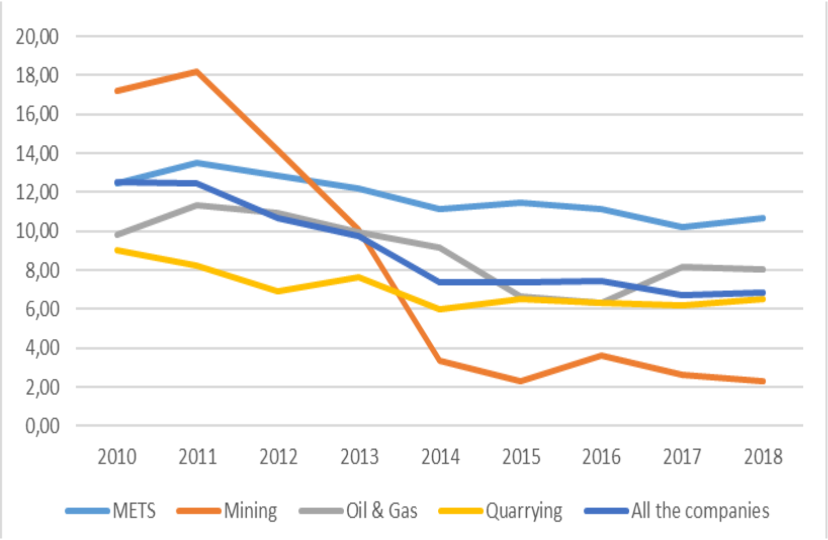
R - Arts, entertainment and recreation	0.02
S - Other service activities	0.02
U - Activities of extraterritorial organisations and bodies	0.01
Total METS %	100

*It regards support services firms for mining and quarrying activities.

Source: Own elaboration on BVD ORBIS dataset.

Appendix C ROE over time of the firms patenting in mining technologies

Figure C – ROE (%) over time of the firms patenting in mining technologies, 2010-2018



Note: ROE = (Net Income/Shareholders Funds) x 100.

Source: Own elaboration on BVD ORBIS dataset.

Appendix D Robustness checks

Table D1 – Mining innovation, technological diversification and profitability: OLS with fixed effects (cross-section analysis year 2012, robustness check)

DEPENDENT VARIABLE: RETURN ON ASSETS (ROA)					
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Log of total assets	0.0069*** (0.0010)	0.0071*** (0.0010)	0.0071*** (0.0010)	0.0071*** (0.0010)	0.0072*** (0.0010)
Log of fixed assets	-0.0063*** (0.0008)	-0.0063*** (0.0008)	-0.0063*** (0.0008)	-0.0063*** (0.0008)	-0.0063*** (0.0008)
Solvency ratio (Shareholders funds/total assets)	0.1456*** (0.0034)	0.1455*** (0.0034)	0.1456*** (0.0034)	0.1456*** (0.0034)	0.1455*** (0.0034)
Total portfolio of mining patents	-2.1E-05* (1.19E-05)			-0.00001 (1.06E-05)	
Portfolio of **automation** mining patents		-0.0035 (0.0032)			-0.0036 (0.0030)
Portfolio of **blasting** mining patents		0.0032** (0.0016)			0.0032** (0.0016)
Portfolio of **environmental** mining patents		-0.0003** (0.0001)			-0.0002 (0.0001)
Portfolio of **exploration** mining patents		-0.00006 (4.61E-05)			-0.00007 (4.68E-05)
Portfolio of **metallurgy** mining patents		0.0011 (0.0010)			0.0012 (0.0010)
Portfolio of **mining (mine operation)** mining patents		-0.00001 (1.97E-05)			-0.00001 (2.02E-05)
Portfolio of **processing** mining patents		-0.0001 (0.0002)			-0.0001 (0.0002)
Portfolio of **refining** mining patents		0.00002 (4.22E-05)			0.00001 (0.00004)
Portfolio of **transport** mining patents		0.00004 (2.84E-05)			0.00005** (2.52E-05)
Inverse of the Herfindahl index (in terms of the 9 mining tech fields)			-0.0321*** (0.0080)	-0.0265*** (0.0090)	-0.0181** (0.0089)
Constant	-0.0293*** (0.0099)	-0.0298*** (0.0099)	-0.0260*** (0.0098)	-0.0273*** (0.0099)	-0.0282*** (0.0099)
Time fixed effects	No	No	No	No	No

Country fixed effects	Yes	Yes	Yes	Yes	Yes
Sector fixed effects	Yes	Yes	Yes	Yes	Yes
No. of observations	36,017	36,017	36,017	36,017	36,017
R^2	0.2153	0.2157	0.2154	0.2155	0.2158

Standard errors clustered by firm in parenthesis.

* p<0.1, ** p<0.05, *** p<0.01

Note: Automation + blasting + environmental + exploration + metallurgy + mining (mine operation) + processing + refining + transport “sub-portfolios” of mining patents = Total portfolio of mining patents.

Note: We replicated this cross-section analysis also for the years 2010, 2011, 2013, 2014, 2015, 2016, 2017 and 2018. The findings are always similar to these ones. We chose to show only the cross-section analysis for the year 2012 for reasons of space. However, the other cross-section analysis are available upon request.

Source: Own elaboration based on ORBIS and WIPO Mining Database.

Table D2 – Mining innovation, technological diversification and profitability: fixed effects model (time span 2010-2018), robustness check)

DEPENDENT VARIABLE: RETURN ON EQUITY (ROE)					
	Model 1	Model 2	Model 3	Model 4	Model 5
Log of total assets	0.0142*** (0.0006)	0.0143*** (0.0006)	0.0144*** (0.0006)	0.0144*** (0.0006)	0.0145*** (0.0006)
Log of fixed assets	-0.0127*** (0.0005)	-0.0127*** (0.0005)	-0.0127*** (0.0005)	-0.0127*** (0.0005)	-0.0127*** (0.0005)
Solvency ratio (Shareholders funds/total assets)	-0.0480*** (0.0022)	-0.0479*** (0.0022)	-0.0478*** (0.0022)	-0.0476*** (0.0022)	-0.0478*** (0.0022)
Total portfolio of mining patents	-0.00001* (9.18E-06)			-7.79E-06 (7.03E-06)	
Portfolio of **automation** mining patents		-0.0024 (0.0017)			-0.0025 (0.0015)
Portfolio of **blasting** mining patents		0.0022** (0.0009)			0.0024** (0.0010)
Portfolio of **environmental** mining patents		-0.0003** (0.0001)			-0.0001 (0.0001)
Portfolio of **exploration** mining patents		-0.00005** (0.00002)			-0.00006** (0.00002)
Portfolio of **metallurgy** mining patents		0.0017* (0.0010)			0.0019* (0.0010)
Portfolio of **mining(mine operation)** mining patents		-7.42E-06 (0.00001)			-0.00001 (0.00001)

Portfolio of **processing** mining patents		0.0002 (0.0002)			0.0003 (0.0002)
Portfolio of **refining** mining patents		-0.00004 (0.00003)			-0.00007* (0.00004)
Portfolio of **transport** mining patents		0.00003 (0.00008)			0.00005 (0.00008)
Inverse of the Herfindahl index (in terms of the 9 mining tech fields)			-0.0392*** (0.0067)	-0.0361*** (0.0073)	-0.0321*** (0.0073)
Constant	0.2647*** (0.0580)	0.2641*** (0.0581)	0.2625*** (0.0580)	0.2626*** (0.0579)	0.2623*** (0.0581)
Time fixed effects	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Sector fixed effects	Yes	Yes	Yes	Yes	Yes
No. of observations	258,767	258,767	258,767	258,440	258,767
R^2	0.0888	0.0890	0.0890	0.0882	0.0891

Standard errors clustered by firm in parenthesis.

* $p<0.1$, ** $p<0.05$, *** $p<0.01$

Note: Automation + blasting + environmental + exploration + metallurgy + mining (mine operation) + processing + refining + transport “sub-portfolios” of mining patents = Total portfolio of mining patents.

Source: Own elaboration based on ORBIS and WIPO Mining Database.