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

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Abstract

This paper uses patent citation networks to study technological change in the mining industry between 1970 and 2015. The analysis is undertaken at both the aggregate level by jointly considering all mining-related technological fields, and at the micro-level of patents in nine sub-fields, representing specific technological "sub-trajectories".

Consistent with previous literature focused on other technological domains, we find that innovation patterns in the mining sector are "technology bounded", i.e. 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 reflecting a highly concentrated oligopolistic structure, hence characterising trajectories as "applicant bounded".

Similar results are observed at the level of sub-trajectories, although with some relevant exceptions, hence suggesting that a substantial heterogeneity exists within the industry and across mining-related technologies.

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

Keywords

Technological trajectories; Technological sub-trajectories; Mining technologies; Geography of innovation; Patents; International technological frontier

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1 Introduction

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 (Iizuka, Pietrobelli and Vargas, 2021). Mining firms have little incentives to differentiate through product innovation or branding. Most innovations are related to cost-cutting processes. As a result, mining firms source new technologies from their own production engineering departments or through technology embedded in products and services obtained from specialised suppliers (Pavitt, 1984).

From a different perspective, Daly, Valacchi and Raffo (2019) emphasise 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 exhibited 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).

The partially contradictory and inconclusive evidence on the technological profile of the mining industry calls for more systematic evidence on the nature and intensity of mining related inventions: How do inventive activities evolve over time in relevant technological fields? Which are the most dynamic technological fields and how are they shaping technological trajectories in this industry? How geographically spread are inventive activities and which are the main actors involved in the global technological development of the industry?

Answering these questions is of paramount importance to address the more general issue of innovation and growth opportunities associated with the specialisation in natural resource production and commercialisation, especially in the case of least developed economies (Andersen et al., 2015). In fact, there is growing awareness in the literature that natural resource-based specialisation does not per se guarantee a high growth, and can even lead to the further impoverishment of countries in case they are unable to master innovation in key mining related technologies (Katz and Pietrobelli, 2018; Perez, 2015). Technological change may affect the economic structure through input–output relationships between sectors, such as a change in final product prices due to a change in the prices of intermediate products. The process of creating new products that replace old ones, in the Schumpeterian process of creative destruction, and the long-term changes in the economy and society due to the emergence of new technological–economic paradigms, also have an impact on the structure of the economy (UNCTAD, 2021).

The technological and economic changes taking place in the core countries of the global system and the leading corporations of the mining industry on the international technological frontier determine the context in which catching up takes place (Bell, 2006). Only through a clear understanding of their changing interests and needs, and of one's own advantages and assets, can opportunities be identified and development ladders constructed and climbed (Perez, 2010). The oil industry has made an enormous amount of technological advances in all value chain stages, from exploration to final processing, and the same can be said about mining and agriculture (Marin, Navas-Aleman and Perez, 2015). However, the important question of this paper is which technical changes in the mining industry took place on the technological frontier, and by which companies and countries and under what conditions have such fundamental innovations been made in which periods.

This paper examines the patterns of inventive activities in mining technologies as captured by patent citation networks. In other words, consistent with a classic view of technical progress as characterised by breakthroughs opening up patterns of cumulative change (Fagerberg and Verspagen, 2021), we use patent citations to illustrate technological trajectories characterising mining related inventions over time. A technological trajectory can be referred to as a set of sequential incremental improvements of technology identifying a specific and collective direction in technological space. This direction is shaped by both technological opportunities and the economic incentives that the market provides (Nomaler and Verspagen, 2019). 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 an innovation's technological significance, as they generally appear to be highly correlated with other measures of the value of innovations as assessed by experts of the relevant technological domain (Jaffe and Trajtenberg, 2002).

The analysis of the connectivity of patent citation networks allows for the identification of technologically significant patents, the ones belonging to the (top) main paths of the citation networks. A (top) main path is a key knowledge flow related to the development of a technological field based on patent citations over a given period of time (Chen, Shih and Liu, 2020).

One of the advantages 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, with benefits for academics, practitioners, and policymakers. 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).

Technological sub-trajectories emerge in the continuum of incremental and radical innovations and provide opportunities for substantial and complementary improvements of the trajectory (Durand, 1992). Kalthaus (2019) points out that analysing technological change at the sub-trajectory level can be a useful complement to considering overall trajectories, since significant innovation occurring in specific technological fields may not be detected when broader technological domains are considered[1]. In other words, investigating sub-trajectories provides a deeper understanding of sectoral innovation patterns. As a first step in our analysis, we identify the technological trajectory for the aggregate of mining technologies. 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[2]. These nine sub-networks, corresponding to the nine technological fields into which mining technologies are divided, represent our

[1] 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. This may mean that a patent can be very important, but not cited within the narrow sub-trajectory.

[2] 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.

nine 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 – a tool to evaluate and describe technological change - which is a network method (for global search) proposed by Liu and Lu (2012) to identify technological trajectories, a proxy for identifying which mining technologies, regions and players (firms) lay on the international technological frontier in mining from 1970 to 2015.

Global main path analysis is useful to identify major paths and critical bottlenecks which will eventually determine path dependent patterns of invention characterising the evolution of mining technologies. 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 (Wang et al., 2020). By extracting the most significant sequence of patents, global (top) main path analysis allows the identification of the key technological bottlenecks. In the case of mining technologies, we find that technological change (on the international technological frontier) is largely shaped and constrained by technological developments occurring in a limited number of technological fields; hence, it is characterised by a high degree of "technology boundedness".

This emphasis on the role played by technical unbalances and constraints characterising a given technology and shaping the rate and direction of technical change has a long tradition in the literature (Rosenberg, 1976) and has paved the way to the analysis of technological trajectories in several domains (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 approach thus examines whether the geographical diversification of innovation patterns is limited by the 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 attempted 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 that developing resource-abundant countries are not on the international technological frontier in mining. 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, as indicated by information on where these patents are filed[3] (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 towards these countries, the extent of upgrading and technological development in mining in developing and emerging countries may be limited, possibly hindering their development opportunities.

Second, we examine whether and to what extent technological change is also "applicants bounded", by exploring the variety of applicants involved in technological developments at the technological frontier.

[3] 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).

The question here is whether there may be some 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 (path dependence) 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. Hence, there seems to be a certain selectivity at the firm level (Filippin, 2021; Verspagen, 2007). Therefore, certain firms help develop the trajectory and the way in which the trajectory unfolds 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 organised 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 utilised. Section 5 illustrates the results concerning the technological trajectory and the technological sub-trajectories in mining technologies. Section 6 concludes.

2 Technological trajectories and technological sub-trajectories: conceptual backgrounds

2.1 Technological trajectories

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 solutions to problems (Mina et al., 2007).

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.

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 through the evolution of patent citation networks.

Technological trajectories can thus be identified as 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).

2.2 Technological sub-trajectories

While technological trajectories summarise 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 emphasising 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) analyses the development of sub-trajectories for insulin production, public switching in telecommunication, dynamic random-access memory and semiconductors.

A potential shortcoming of our approach to identify the top knowledge flow (i.e. top main path) of sub-trajectories in the mining industry is that we only consider patent citations within each sub-trajectory, meaning that a patent can be very important, but not cited within the narrow sub-trajectory. 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 favours emerging sub-trajectories that show favourable 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).

In Sections 2.3, 2.4 and 2.5, we illustrate our three research questions regarding which technologies, regions and players (companies) are on the international mining technological frontier (i.e. top main path of the trajectory and sub-trajectories). In other words, we examine whether and to what extent the mining frontier is technology, geography and applicant bounded.

2.3 Technological boundedness

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) with reference 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.

Adopting such an approach it is often found that main paths are "technology bounded", meaning that 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). For example, in the case of mining technologies, technological change can be technology bounded if the trajectory unfolds only along very few mining technological fields (among the nine fields that constitute the core of the mining industry).

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).

2.4 Geographical boundedness

Building on the existing literature that has largely focused on the question of technological boundedness (see for instance Fontana, Nuvolari and Verspagen, 2007; Verspagen, 2009; Kalthaus, 2019), we undertake a relatively new research avenue to examine whether and how innovation patterns are "geographically bounded", in terms of national sources (origin of applicants and inventors).

Geographical diversification of innovation patterns is limited by the territorial proximity of inventors and by the 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 on the frontier.

This would highlight that developing resource-abundant countries lag behind the international mining technological frontier. Specifically, countries that operate far behind the technological frontier usually do not have the resources to invest in technological congruence and social capability to absorb international knowledge flows, nor the expertise to implement a successful policy to make absorption of knowledge possible[4]. This is why they have a high probability to remain at low levels of development (Fagerberg and Verspagen, 2021; Verspagen, 1991). In fact, sustained economic growth requires, among other factors, constant technological improvements (Dosi and Nelson, 2013; Lavopa and Szirmai, 2018).

2.4 Applicant/player boundedness

The third research question aims to explore the degree of heterogeneity in technological change on the technological frontier in terms of different applicants. Thus, we will examine the extent to which the same applicants (firms) concentrate in their hands the crucial patenting activities

We will look at the selectiveness (Verspagen, 2007) of the technological trajectories at the firm level by checking whether the top main path we identify in the field of mining technologies is the result of a selective process through which only a few organisations added to the path. More specifically, we will find out whether those mining patents that we will identify as belonging to the top main paths in the development of mining technologies involve a limited set of all organisations active in global mining innovation, or whether they are just a random sample of all organisations active in mining innovation (Filippin, 2021). 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).

The three different dimensions of boundedness in terms of technology, geography and applicants are inter-related. For instance, applicant boundedness may imply geographical boundedness, to the extent that key technologies originating the main innovation path are geographically concentrated. Furthermore, an insight from our analysis is that new players may emerge in the transition from an established technological paradigm to a new one (i.e. from exploration towards environmental technologies). This

[4] In our analysis, we do find a lack of diffusion of frontier mining technologies across countries.

raises an interesting question of whether it is new firms that lead to jumps to new paradigms (easing technological boundedness), or whether there are other causal links.

3 Data

3.1 Dataset description

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[5] 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). One of the main reasons for the split of mining technologies into the nine sub-trajectories is to distinguish innovation activities from upstream to downstream stages along the mining value chain. The WIPO Mining Dataset also contains information, among others, about where the mining patents are filed (application authority), along with the geographical origin (at the country level) of inventors and applicants.

It is worth pointing out that each mining technological field (sub-trajectory) can be 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). We take into account of these sub-fields when analysing the top main path of the nine sub-trajectories, in order to assess whether the sub-trajectories are technologically, geographically and applicant bounded.

The dataset is composed of 486,579 mining patents (nodes) that are connected to each other through 1,669,306 citations, i.e. edges of the largest component[6] of the network. Appendix C provides some descriptive statistics regarding the distribution of the nodes (mining patents) of the largest component of the network in terms of the nine mining technological fields (sub-trajectories) across years.

Table 1 reports some descriptive statistics of the degree of citations received and made by the mining patents (nodes) that belong to the largest component of the network. As depicted in Table 1, most nodes receive and/or make few citations and few nodes receive and/or make many citations. Additionally, Figure 1 reports the number of citations received and made over time, revealing that the number of

[5] 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.

[6] In network theory, the largest component is a connected component of a given network of patent citations that contains a finite fraction of the entire network's nodes, i.e. patents in our case (De Nooy et al., 2018).

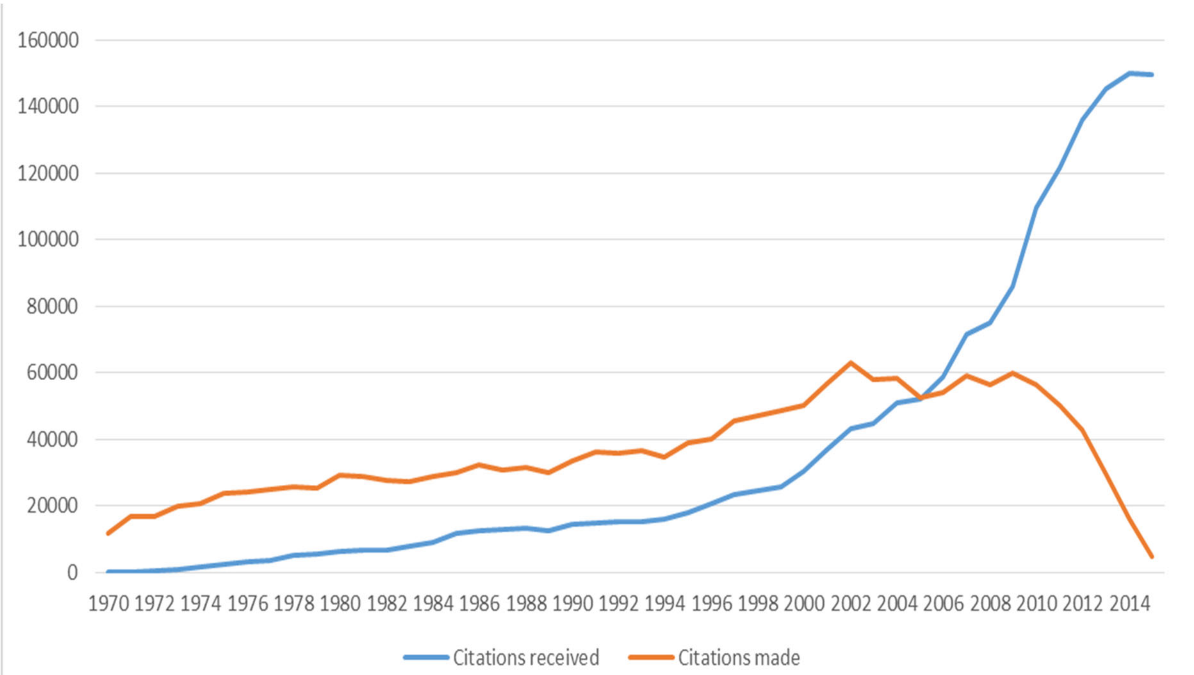
citations received has been lower than the number of citations made until year 2005. Then, the number of citations received and made registered an opposite trend from year 2005 onwards. Specifically, the number of citations received had a sharp increasing trend after 2005, whereas the number of citations made registered a declining trend in the latter period. Furthermore, Table 2 shows the distributions of citations received and made among the nine mining technological sub-trajectories. It turns out that the mining sub-trajectories, i.e. mining technological fields with the highest shares of citations are exploration, mining (mine operation), refining and environmental.

Table 1 – Descriptive statistics of citations received and citations made

	Citations received	**Citations made**
Minimum	0	0
25th Percentile	0	0
50th Percentile	2	1
75th Percentile	4	3
90th Percentile	7	8
95th Percentile	11	15
99th Percentile	37	43
Maximum	470	398
Mean	3.430699	3.430699
Standard Deviation	8.128543	9.318987

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

Figure 1 – Number of citations received and made over time, 1970-2015



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

Table 2 – Distribution of citations made and citations received across the mining technological sub-trajectories (i.e. mining technological fields)

Mining sub-trajectories (mining technological fields)	Number of citations made	Percentage of total citations made	Number of citations received	Percentage of total citations received
Automation	582	0.03	647	0.04
Blasting	19214	1.15	29388	1.76
Environmental	179386	10.75	178329	10.68
Exploration	772558	46.28	763557	45.74
Metallurgy	7004	0.42	5732	0.34
Mining	355487	21.30	354097	21.21
Processing	53419	3.20	58631	3.51
Refining	227175	13.61	226085	13.54
Transport	54481	3.26	52840	3.17
Total citations	1669306	100	1669306	100

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

3.2 General trends of mining innovation

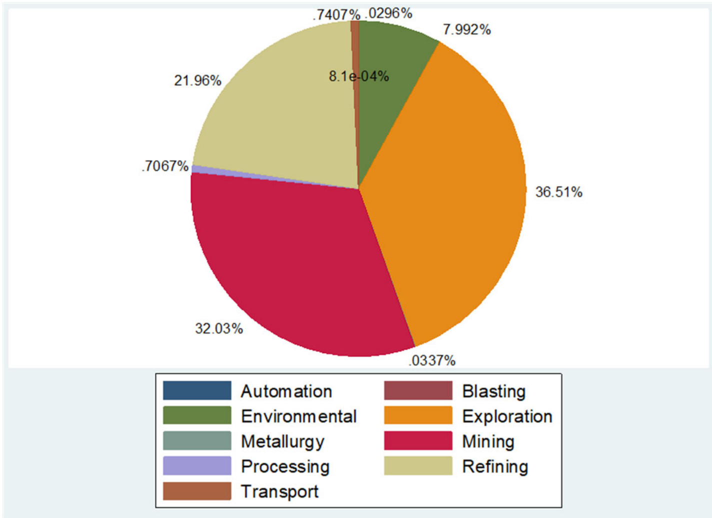
In this section we provide some initial descriptive statistics on the composition of patents in mining and developments over time. In doing so, we pay attention to the three dimensions that we consider relevant when discussing technological trajectories, namely technological, geographical, and applicants.

3.2.1 Technological perspective

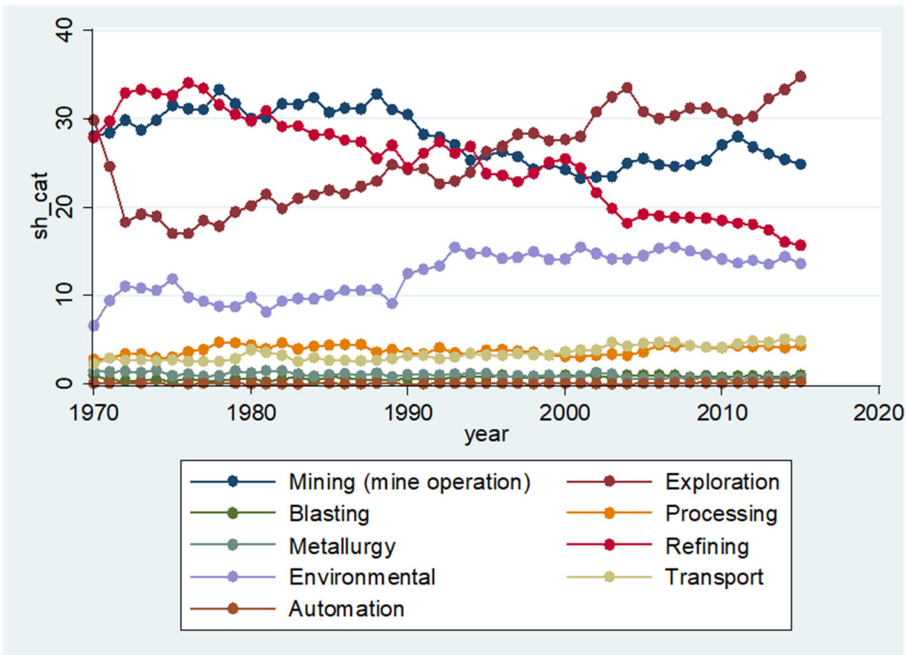
We begin by looking at the technological fields in which mining patents are taken out, in particular, considering the 9 technological fields (within mining) identified above. In Figure 2 we report information on both the share of patents over the period 1970-2015 in the different subfields and developments in patenting in these different subfields over time.

Figure 2 – 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.

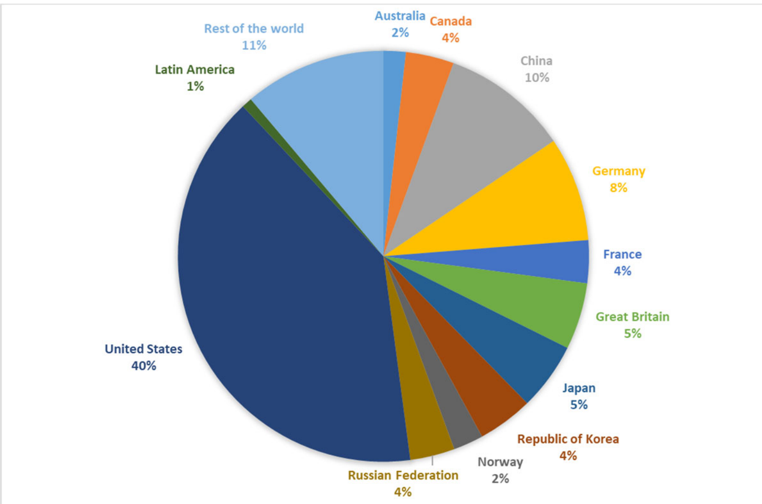
Figure 2a shows that the bulk of global mining innovation (98.5%) is concentrated in four mining technological fields: mining (mine operation) (32.03%), exploration (36.51%), refining (21.96%) and environmental (7.99%). The remaining 1.5% is distributed among processing, transport, metallurgy, blasting 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 2b shows that, in particular, after 1990, the shares of refining and mining show a declining trend[7]. 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 shares 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.

3.2.2 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, i.e. individuals (OECD, 2009).

Figure 3 – 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 1% each.

Source: Own elaboration on WIPO Mining Database.

Results in Figure 3 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

[7] This may also be due to the fact that refining and mining have shown an increasing trend, but that other segments have grown more rapidly (indicating a declining share for refining and mining).

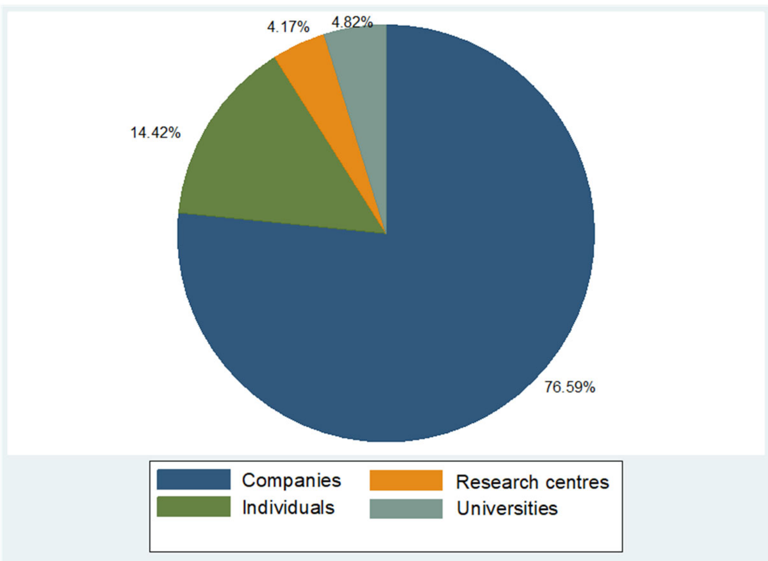
innovation according to these data, despite these countries heavily relying on mining production (Iizuka, Pietrobelli and Vargas, 2019).

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.

3.2.3 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 4 below).

Figure 4 – 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 centres (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 3 reports information on the main actors (applicants) in terms of global mining innovation (measured by patents). Table 1 documents all organisations in the database that hold more than 950 mining patents.

There are 27 organisations, 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 organisations in mining innovation are almost entirely companies is coherent with Figure 4, since companies are the most active applicants in terms of mining patenting activity. 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[8].

Table 3 – Number of patents per company or organisation in the mining patents database (largest component), 1970-2015

Rank	Type of applicant*	Organisation 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

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

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 based on WIPO Mining Database.

4 Methodology: global main path analysis

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).

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 our analysis, 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.

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[9] is a type of "traversal count" which measures the times a 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 X in patent Y is obtained as follows. First, one needs to count all patents in the network for which a path to X exists

[9] 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 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).

(including X itself). Then, one has to count all patents that can be reached from patent Y (including Y itself). The SPNP value associated to the citation of patent X in patent Y 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 D 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 emphasising 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). Specifically, we identify for every start-node in the network the path (ultimately leading to an end-node) that maximises the multiplication (sum of logs) of the SPNP values along the path. Such a path is called "main path[10]". 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 emphasises the overall importance in knowledge flow[11]. 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. Hence, the TMP is a better approach than the NMP for our analysis aimed at detecting technologies, regions and players on the international mining technological frontier. Nomaler and Verspagen (2019) argue that the NMP or TMP that is generated by the priority first search algorithm consists of a subset

[10] "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)).

[11] 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.

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[12].

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.

5 Results

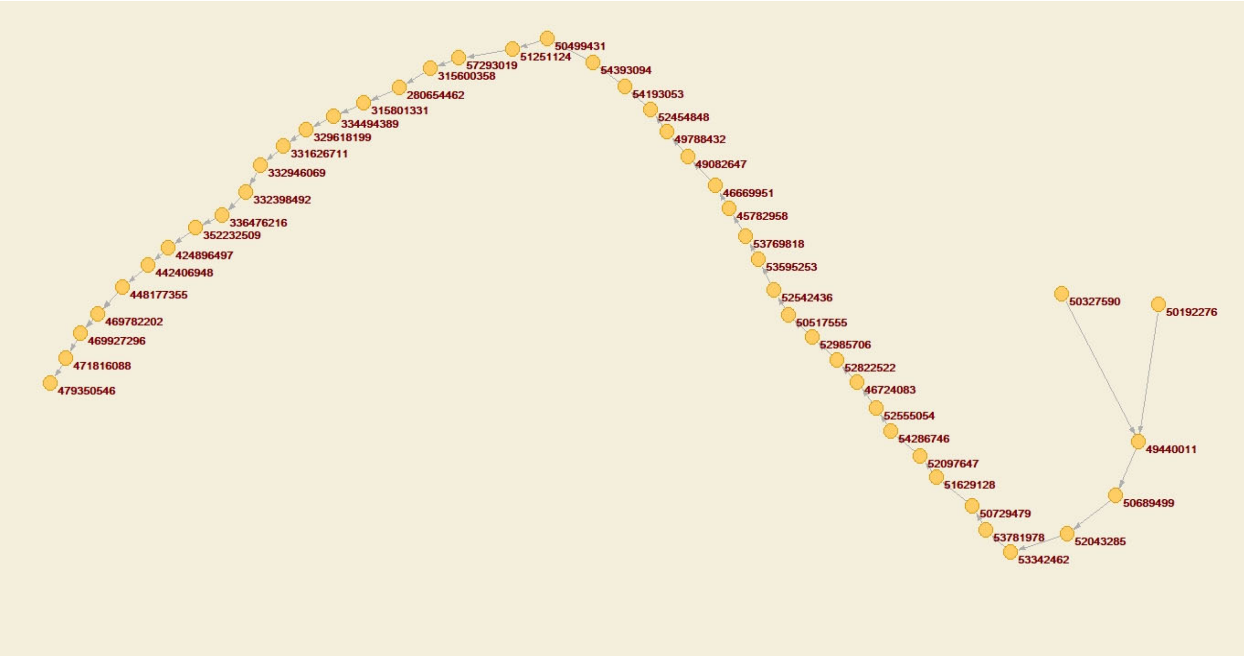
5.1 Mining technological trajectory

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[13]. 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 5 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.

[12] 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.

[13] 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.

Figure 5 – 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.

Table 4 – "Core" mining patents present in the technological trajectory in chronological order starting from the right side to the left side of Figure 5

	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 3) are in bold.

Source: Own elaboration.

Figure 5 indicates that there are 43 mining patents present in the top main path. These 43 "core" mining patents are listed in Table 4. 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 on the international mining technological frontier 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[14] 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[15].

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"[16]), 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 utilising 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. In fact, at the beginning of the period technological change unfolded along

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[14] 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).

[15] 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 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.

[16] 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.

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 on the frontier 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).

5.1.1 Technology boundedness

Answering our first research question (Section 2.3) of whether the top main path is "technology bounded" or not at the trajectory level (i.e. the international technological frontier), 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, i.e. there are only patents belonging to these two mining-related technologies on the technological frontier. Relatedly, and more precisely, the number of patents regarding the other 7 mining-related technologies (is not present and) did not develop on the technological frontier during the same time span. 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 analyse below the role played by economic and institutional factors in the selection and establishment of those two technological paradigms. 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 mineralising 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[17] (i.e. the presence of continuity and cumulativeness in that portion of the main path).

As for 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 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, 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 (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, desulphurisation techniques to limit SO2 emissions and underground mining technologies to minimise land disruption (Hilson, 2002).

Clean technologies are characterised 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[18]. This likely contributes to confirm the fact that firms are compelled to innovate in environmental technologies by public policies.

[17] 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).

[18] 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.

5.1.2 Geography boundedness

Switching attention to the geographical dimension (answering our second research question in Section 2.4), and focusing on the country of residence of the applicant as depicted in the penultimate column of Table 4), 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, technological change on the international technological frontier 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[19] for 95% of applicants and 100% of inventors.

It is worth emphasising 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.

This scenario confirms that developing resource-abundant 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 4 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.

5.1.3 Applicant boundedness

In terms of applicants (third research question in Section 2.5), the top main path is shaped by 43 mining patents invented by companies[20] (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 on the international frontier 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 4, 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

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

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

Table 3). 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[21] 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 3 and 4 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.

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).

5.2 Mining technological sub-trajectories

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.

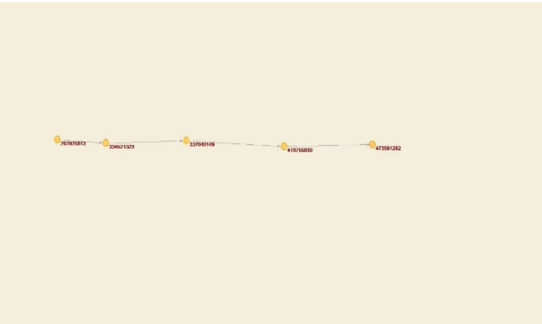
It is worth remembering that technological sub-trajectories do not need to intersect with the overall technological trajectory (Kalthaus, 2019), as it happens in our case. This means that the "core" mining patents in the TMP at the sub-trajectory level are totally different from the ones present at the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

[21] Analysing 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).

Figure 6 portrays the findings related to the identification of the TMP regarding 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 6 - TMP technological sub-trajectories in mining technologies globally[22], 1970-2015

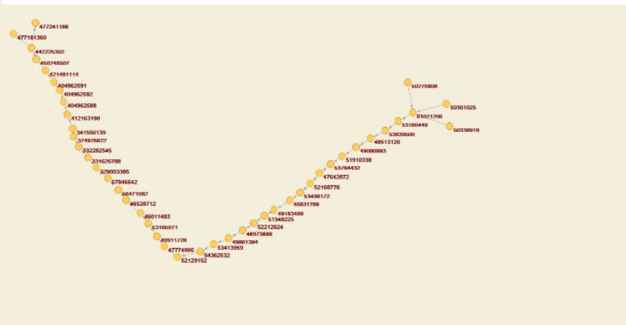
a) Automation



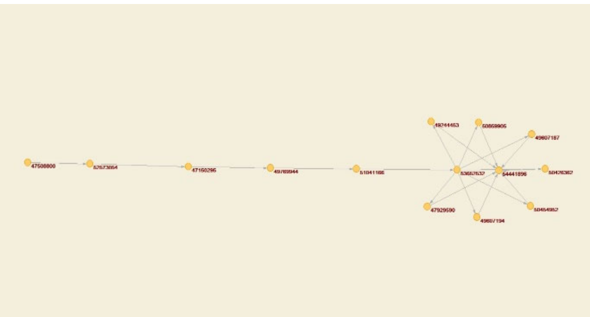
b) Blasting

c)Environmental

d)Exploration



e) Metallurgy



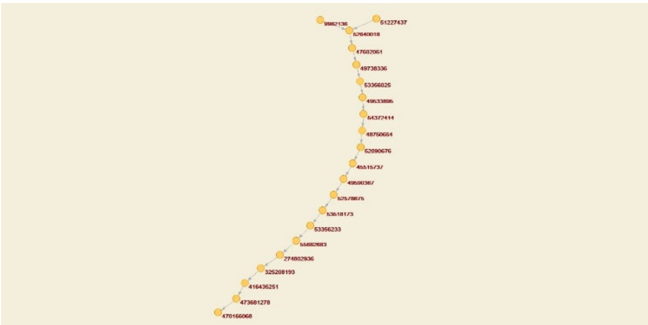
f) Mining (mine operation)

[22] 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 4 at the trajectory level) are illustrated in 9 tables that are in appendix E.

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[23] 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 2). Metallurgy and above all automation are the sparsest sub-trajectories, but they also have a negligible role in the entire dataset (Figure 2).

5.2.1 Technology boundedness

First, we can provide comparisons between what happens at the trajectory level and at the sub-trajectory level[24]. In fact, it may sometimes happen that different technological paths emerge (Kalthaus, 2019). It is

[23] 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 2). For the sake of completeness, metallurgy is the second sub-trajectory that started to develop lately from 1998 and it stopped evolving on 2007.

[24] 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.

worth emphasising 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 6d, 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 characterised 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[25], 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 F 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.

5.2.2 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-trajectories[26]. The exercise follows the same methodology of Section 5.1 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.

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).

[25] 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 G 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.

Answering our second research question in Section 2.4, it turns out that the same geographical pattern is confirmed at the sub-trajectory level, with only few exceptions. Table 5 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 5 - 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 5 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 shaped by US companies, with the partial exception of the mining (mine operation), transport and (especially) processing sub-trajectories.

Table 5 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 5.

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 H in Appendix H 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%.

5.2.3 Applicant boundedness

The third stage is to figure out whether technological change at the sub-trajectory level is "applicant bounded" (third research question in Section 2.5). 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 E). Specifically, the sub-trajectory metallurgy is shaped by only one company, while just two out of the 14 firms that characterise 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 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 5.2.2). 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 E for details on this).

6 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 international technological frontier in mining. Relatedly, and more precisely, patents within the other seven mining-related technologies are not found on the technological frontier during the same time period. 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) are due to different reasons. Specifically, the focus on exploration technologies is largely led by economic interests of firms (reduction of costs and uncertainties); whereas, the development of environmental innovations at the trajectory level is more motivated by institutional factors, i.e. stricter governmental policies aimed at coping with environmental challenges faced by the mining industry.

We find that 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 on the frontier in mining technologies, in addition to being "technology bounded", is also "geographically bounded". This reveals that developing resource-abundant 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.

We also showed that 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 (Filippin, 2021; Verspagen, 2007), i.e. a small number of companies 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.

In Section 5.2, we have examined whether technological change is technology, geographically and applicant bounded at the level of the 9 mining sub-trajectories. The environmental and exploration sub-trajectories exhibit 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, also 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). However, we also find that blasting and refining sub-trajectories are significantly less technology bounded.

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.

Developing economies appear to dramatically lag behind in terms of inventive activities as they do not participate to patenting at the technological frontier in mining, which represents a key domain of specialisation in many of these countries[26]. This might have negative implications for their long run economic growth.

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.

We have highlighted 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 also 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 any significant 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

[26] Even taking into account its limited potential in creating employment, in comparison to the manufacturing sector (Haraguchi et al., 2017; Dosi and Tranchero, 2021).

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 analyse 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 organisational 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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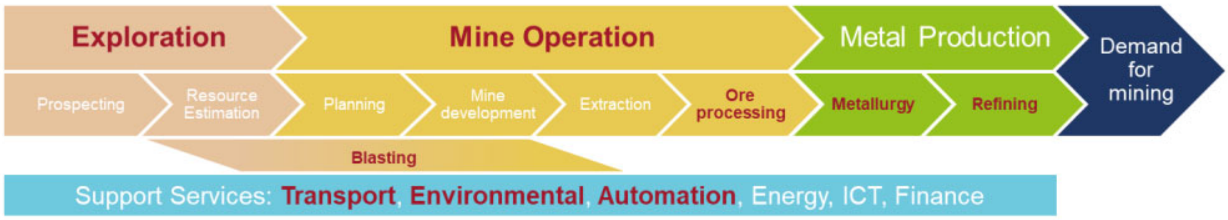
Appendix A Mining GVC stages

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				Assays	Extraterrestrial	Control	

		mineral processing							
		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 Distribution of mining patents in terms of mining technological fields across years

Table C - Number of mining patents (nodes) of the network's largest component per each mining technological field (sub-trajectory), 1970-2015

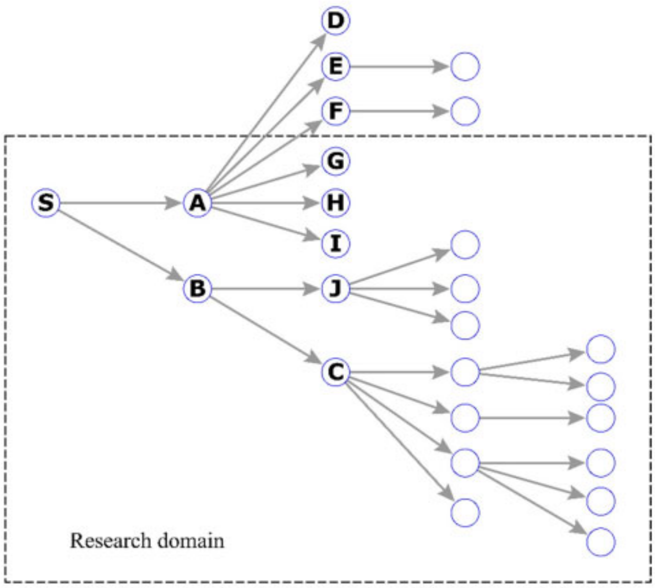
Year	Automation	Blasting	Environmental	Exploration	Metallurgy	Mining (mine operation)	Processing	Refining	Transport	Total mining patents
1970	1	17	115	516	26	485	48	482	40	1.730
1971	2	13	269	698	39	806	82	843	83	2.835
1972	0	13	372	615	48	1.002	114	1.107	89	3.360
1973	2	15	409	725	50	1.083	128	1.257	103	3.772
1974	0	20	429	769	64	1.211	121	1.334	107	4.055
1975	0	15	559	799	44	1.481	143	1.535	128	4.704
1976	1	31	497	860	58	1.576	185	1.724	130	5.062
1977	4	17	462	914	44	1.534	192	1.653	125	4.945
1978	0	19	472	961	49	1.795	254	1.703	136	5.389
1979	3	32	470	1.049	82	1.709	251	1.645	154	5.395
1980	1	35	555	1.139	69	1.695	250	1.683	222	5.649
1981	2	16	471	1.239	87	1.741	229	1.786	208	5.779
1982	1	32	538	1.139	86	1.823	268	1.673	189	5.749
1983	1	45	542	1.172	62	1.765	222	1.629	142	5.580
1984	0	21	556	1.230	50	1.863	245	1.623	170	5.758
1985	3	49	614	1.340	64	1.874	267	1.726	164	6.101
1986	2	48	666	1.350	74	1.960	281	1.733	168	6.282
1987	1	32	631	1.332	56	1.857	266	1.630	154	5.959
1988	3	27	641	1.372	74	1.961	216	1.528	159	5.981
1989	0	28	523	1.422	48	1.777	225	1.547	164	5.734
1990	0	35	772	1.498	66	1.884	219	1.512	199	6.185
1991	1	37	786	1.479	65	1.714	207	1.582	197	6.068
1992	5	39	801	1.357	61	1.673	247	1.642	171	5.996
1993	5	41	930	1.380	67	1.626	213	1.569	182	6.013
1994	4	53	857	1.391	68	1.472	201	1.559	201	5.806
1995	3	49	922	1.625	72	1.602	236	1.472	204	6.185
1996	3	68	957	1.813	56	1.772	265	1.590	219	6.743
1997	4	49	1.036	2.041	70	1.861	269	1.655	250	7.235
1998	3	51	1.112	2.104	67	1.804	266	1.769	249	7.425
1999	8	66	1.131	2.207	78	1.992	257	2.013	266	8.018
2000	4	86	1.232	2.408	66	2.110	270	2.219	319	8.714
2001	5	91	1.506	2.726	94	2.266	305	2.380	372	9.745
2002	2	94	1.497	3.117	133	2.371	328	2.188	390	10.120
2003	4	80	1.468	3.356	117	2.433	352	2.057	485	10.352
2004	4	112	1.592	3.769	70	2.807	373	2.046	480	11.253
2005	7	123	1.763	3.738	77	3.095	445	2.337	554	12.139
2006	13	138	2.133	4.187	89	3.455	612	2.654	658	13.939
2007	20	164	2.538	4.977	117	4.030	689	3.088	774	16.397
2008	20	139	2.682	5.574	111	4.431	772	3.577	772	18.078
2009	35	189	2.978	7.336	139	5.135	837	3.817	838	21.304
2010	26	184	3.477	8.519	145	6.644	1.005	4.537	1.020	25.557
2011	37	248	3.905	9.568	141	8.009	1.227	5.202	1.294	29.631
2012	59	294	4.412	10.561	186	8.459	1.339	5.705	1.553	32.568
2013	69	287	4.440	11.563	205	9.521	1.415	5.697	1.534	34.731
2014	74	267	4.720	11.906	210	9.313	1.344	5.258	1.659	34.751
2015	78	291	4.049	11.363	208	8.402	1.286	4.674	1.456	31.807
Total	520	3800	63487	142204	3952	130879	18966	103640	19131	486.579

Source: Own elaboration based on WIPO Mining Database.

Appendix D 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 E "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 6

Table E1 – 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 3) are in bold.

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

Table E2 – 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 3) are in bold.
Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Table E3 – 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 3) are in bold.

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

Table E4 – 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 3) are in bold.

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

Table E5 – 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 3) are in bold.

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

Table E6 – 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 3) are in bold.

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

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Table E7 – 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 3) are in bold.

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

Table E8 – 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 3) are in bold.
Source: Own elaboration based on WIPO Mining Database and EPO-PATSTAT.

Table E9 – 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 3) are in bold.

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

Appendix F 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 for deactivating a partially flooded perforating gun assembly, and apparatuses aimed at overcoming high pressure or high temperature difficulties.	The first five patents in the TMP of the refining sub-trajectory relate to technologies that usually treat molten aluminium, metals with an impeller. Molten aluminium 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 separation zone. Specifically, three (patents N. 52420139, 53852393 and 52343307) out of these first five patents regard metal scrap melting system.

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.	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 E6 (refining) and E9 (blasting) in Appendix E.

Source: Own elaboration based on EPO-PATSTAT Database.

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

Table G – 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 H Countries where the core mining patents (sub-trajectories) related knowledge diffuses

Table H – 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.

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