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## CO-EVOLUTIONARY PATTERNS OF GVC-TRADE AND KNOWLEDGE FLOWS IN THE MINING INDUSTRY: EVIDENCE FROM LATIN AMERICA

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# Co-evolutionary patterns of GVC-trade and knowledge flows in the mining industry: Evidence from Latin America

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## Abstract

Although evolutionary economics has extensively analysed the evolution of industries in relation to innovation and technology lifecycles, the interplay between industry lifecycles and evolutionary patterns of knowledge networks has not been fully explored yet. This work aims to bridge this gap by analyzing the co-evolutionary patterns of knowledge and trade flows in the mining industry, using social network tools in combination with the Schumpeterian tradition of analysis. The study focuses on three Latin American countries: Brazil, Chile, and Peru, where the mining sector plays a significant role in the economy, particularly in the context of energy and digital transitions. Our findings suggest that the innovation network and the global value chain-trade network display divergent co-evolutionary patterns: while the former tends to be stable and concentrated, the latter shows increasing fragmentation and turbulence. The analysis also shows remarkable evolutionary evidence at the country level.

JEL Codes: L10, L72, O30, F14, N56

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## 1. Introduction

Evolutionary economics has long focused on the dynamic analysis of economic change at the organization and the industry level. A large body of literature in this stream has explored the historical evolution of industries and the interplay with innovation and technology lifecycles (Nelson and Winter, 2002). This specific approach to evolutionary theorizing is rooted in the seminal contributions by Utterback and Abernathy (1975) and Abernathy and Utterback (1978), in which uncertainty concerning technology developments and market penetration affects the dynamics of industry lifecycles in terms of Schumpeterian competition. This framework of analysis has eventually been generalized and further elaborated to enrich its theoretical underpinnings (Klepper and Graddy, 1990; Klepper, 1996 and 1997). Though one can hardly claim its universal validity, the industry lifecycle theory has proved to fit the observed evolutionary patterns of a wide array of industries (Klepper and Simons, 2000; Mowery and Nelson, 1999).

A somewhat less explored avenue of research concerns the interplay between industry lifecycles and evolutionary patterns of knowledge networks. Extant literature has stressed the importance of cumulated technological capabilities and learning dynamics in the decision of incumbents to resort to external knowledge sources to cope with technological discontinuities at the onset of new lifecycles. In the early stage of lifecycles, networking can also ensure the recombinant dynamics across a large variety of domains that are typical of exploration strategies. In the mature stage, networks do not necessarily disappear, but their structure becomes more stable due to the emergence of prominent nodes acting as hubs of knowledge and competencies (Jacobides and Winter, 2005; Chesbrough and Prencipe, 2008; Ozman, 2009; Saviotti and Catherine, 2008; Krafft, Quatraro, Saviotti, 2014).

From an international trade perspective, much literature has focused on the reasons behind the innovation networking strategies of multinational corporations (MNCs). Previous literature has emphasized the importance of gaining access to internationally dispersed technological capabilities to integrate them in recombinant dynamics, leveraging knowledge repositories in geographically dispersed units (Zander, 1999 and 2002). So far, less attention has been given to the interplay between international innovation networks and trade flows, while only recently has some literature emerged addressing the nexus between innovation and international trade by looking at the impact of countries' integration into Global Value Chains (GVCs) on innovation performances (Pietrobelli and Rabellotti, 2011; Lema et al., 2021).

This paper aims to fill these gaps by delving into the co-evolutionary patterns of knowledge and trade flows in the mining industry, with a particular focus on three significant Latin American countries: Brazil, Chile, and Peru. In doing so, we advance our knowledge of these dynamics in many respects. First, we add to the still scant literature analyzing the evolutionary patterns of innovation networks across an industry's lifecycle. Second, we contribute to the debate on the link between the network of trade flows in GVCs and the web of knowledge interactions. Third, we provide fresh evidence about the co-evolution of GVCs and innovation networks in a sector that has recently attracted increasing attention, like mining. Such interest is grounded on the importance that minerals increasingly acquire in the context of energy and digital transitions and the growing adoption of 4.0 technologies, with rising demand in volumes and varieties of minerals. Our focus on Latin American countries is justified by the substantial contribution of this sector to these economies (Iizuka et al., 2022). The mining sector holds significant economic importance in Peru, Chile, and Brazil. It constitutes a substantial share of GDP, exports and workforce in these countries.<sup>1</sup> Peru is a prominent global supplier of metallic minerals, with strong positions in silver, copper, zinc, tin, lead, and molybdenum production. Chile's mining industry is highly focused on copper, contributing significantly to global output. Brazil primarily centers its mining production on iron, while also producing notable quantities of niobium, vermiculite, asbestos, tantalum, and bauxite. These countries have also demonstrated advanced innovation capabilities, as evident in patents, new product development, and technology adoption, as well as exports of goods and services (Pietrobelli et al., 2018). Collectively, these factors make them particularly intriguing cases in Latin America.

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<sup>1</sup> The mining sector contributed 11.7%, 9.9%, and 1.9% to the GDP of Peru, Chile, and Brazil, respectively, in 2015. It also constituted a significant share of their exports, accounting for 21%, 60%, and 46% of total exports. In terms of employment, the sector engaged 4.2% of the workforce in Peru, 2.9% in Chile, and 0.52% in Brazil (Pietrobelli et al., 2018).

To investigate the existence of a co-evolutionary pattern between GVC-trade and knowledge flows, we use network analysis and measure the centrality, stability and concentration of key industries-countries (i.e., nodes) in their respective networks over time. To do this, we use patent data to depict the innovation and knowledge network and value-added trade data to represent the GVC network.

Our results show that the evolution of the innovation network and the GVC-trade network have divergent patterns. The innovation network tends to remain stable and concentrated, whereas the GVC-trade network displays a trend of growing fragmentation and turbulence. The analysis also reveals notable evolutionary patterns at the country level. Collaborative mining innovation activities in Brazil align with the overall pattern, while the GVC pattern differs. Chile's mining technological dynamics are qualitatively similar, with industries exhibiting strengthening dynamics in the GVC network. Peru displays a distinct pattern compared to Brazil and Chile, mainly due to limited mining innovation activities.

The paper is organized as follows. Section 2 recalls the Schumpeterian innovation patterns and the evolution of innovation networks. Section 3 presents some stylised facts on the mining sector's importance in the international dynamics of innovation and trade flows in Latin American countries. Section 4 explains the data and methodology we use, whilst, in Section 5, we present the results of the analysis. Finally, Section 6 concludes.

## 2. Theory development

The Schumpeterian approach to the analysis of innovation dynamics has long emphasized the distinction between two main patterns of innovations i.e., the so-called Mark I and Mark II. Following Malerba and Orsenigo (1995, 1996), these two patterns can also be labelled as 'widening' and 'deepening', respectively. On the one hand, the widening pattern is characterized by a continuously expanding knowledge base, fed by turbulence and entry of new firms ensuring increasing variety. On the other hand, the deepening pattern is featured by low variety and dominance of a few large innovative firms that successfully accumulate technological capabilities. Former research has put forth the idea that these two patterns are sector-specific, as each sector is characterized by idiosyncratic technological regimes, i.e., conditions of appropriability, cumulateness and turbulence (Malerba and Orsenigo, 1996 and 1997). Yet, a complementary strand of literature has emphasized that they can feature the evolutionary patterns of a single sector over the industry lifecycle (Breschi et al., 2000; Malerba and Orsenigo, 1995; Klepper, 1996; Utterback and Abernathy, 1975; Henderson and Clark, 1990).

The evolutionary approach has paid less attention to network dynamics regarding both innovation and production. This is unfortunate, given that external collaborations have grown in importance in the last decades. Innovation networks have gained momentum in view of the increasing complexity of scientific and technological knowledge (Uzzi, 1997; Carnabuci and Operti, 2013; Fusillo et al., 2022), and the globalization process has provided plenty of opportunities for the formation of formal and informal production networks (Parrilli et al., 2013). The few existing contributions addressed the innovation and global production sides only separately. The evolutionary approach to innovation networks highlights the importance of changes in networks' structure in terms of node relevance, entry of new nodes, the establishment of new links, and deactivation of existing links. These dynamics are, in turn, shaped not only by strategic considerations but also by path-dependent processes constrained

by social, institutional, cognitive, and spatial proximity (Broekel and Boschma, 2012; Balland et al., 2013). A key role is played by technological uncertainty, which is shaped by the nature and scope of technological change and its relationship with extant capabilities (Langlois, 1992; Robertson and Langlois, 1995). Accordingly, in the so-called era of ferment, the structure of existing firms' networks changes to involve the new entrants and activate learning by interacting dynamics (Anderson and Tushman, 2018). In this context, one would observe the growth of innovation networks above all in terms of the appearance of new nodes and the emergence of new central actors. As the lifecycle approaches maturity, competence-enhancing technological change reduces uncertainty and hence the turbulence in both industrial dynamics and the structure of innovation networks. A few nodes emerge as leaders in the market, and the hierarchy of central innovators becomes increasingly stable, leading to a concentration of collaborative innovation activities (Rosenkopf and Tushman, 1998; Krafft et al., 2011 and 2014).

The literature on global production networks (GPNs) and GVCs has largely overlooked the analysis of the dynamic evolution of network structure. Yeung and Coe (2015) have stressed the importance of three main factors in shaping firms' strategies to search and manage global linkages, i.e., optimizing the cost-capability ratio, market development and interactions with the financial sector. Depending on the nature of risks and uncertainty that firms face, these three forces interact and engender different configurations of global networks. Recent contributions show that the study of the relationship between GVCs and innovation activities can be fertile and enrich the understanding of the dynamics at stake. Extant literature investigates the impact of the involvement in GVCs on innovation dynamics and the development of technological capabilities (Pietrobelli and Rabellotti, 2011; Lema et al., 2021). The international trade literature has shown how the international fragmentation of production and the rise of GVCs can alter the domestic organization of production also within industries (Feenstra and Hanson, 1996; Deardorff, 2001; Grossman and Rossi-Hansberg, 2008). The literature also highlights knowledge spillovers associated with trade, particularly in the context of international fragmentation of production (Keller, 2004). Compared to other knowledge spillover channels based on traditional trade flows, GVC-led trade is expected to have a stronger spillover effect (Piermartini and Rubinova, 2014; Foster-McGregor et al., 2016).<sup>i</sup>

The analysis of the interplay between the evolutionary dynamics of innovation and GVCs networks has been little explored and can be very promising. In this direction, we hypothesize that the relationship between GVCs and innovation can exert mutual influences on the structure of the knowledge and production networks, and on their evolutionary patterns, and possibly co-evolve.

Following the Schumpeterian tradition of analysis, three main dimensions deserve attention, incorporated in the novel application to networks, i.e., the stability of nodes' hierarchy, the concentration of ties around a few nodes, and the entry/exit of (new) nodes from the network (Breschi et al., 2000; Krafft et al., 2011). Thus:

- In the Schumpeter Mark I, the 'widening' pattern is driven by exploration dynamics featured by the entry of new nodes into the network, which leads to the reconfiguration of its structure through reduced concentration and high turbulence (changing hierarchy of nodes);
- In the Schumpeter Mark II, the 'deepening' pattern is associated with the selection of a dominant design which paves the way to the exploitation of technological and economic

opportunities, followed by reduced turmoil and the emergence of a stable hierarchy of nodes and of clusters featured by dense connections.

While the co-evolution of these three dimensions may help identify the two kinds of Schumpeterian patterns, many more configurations can also be found, and the empirical analysis will reveal different nuances.

### 3. The Empirical context

Although historically the mining sector was not seen as a driving force for growth, it represents a significant share of the economies of many emerging countries. Now, however, some authors argue that new opportunities could emerge for these countries as the industry experiences increasing outsourcing and offshoring in resource-intensive industries (Pietrobelli et al., 2018), and as scientific and technological developments become more pervasive (Iizuka et al., 2022).

#### 3.1 Innovation in mining

Innovation is an intrinsic part of the mining industry, as confirmed by expenditures in R&D and patents, together with GVC integration (Daly et al., 2019). Recent research suggests that these trends are creating new opportunities for innovation and linkages between lead firms and suppliers (Perez, 2010; Andersen, 2012; Marin et al., 2015). Demand for natural resources, new knowledge and technology, outsourcing, and the pressure to reduce environmental impact all contribute to a positive outlook for mining countries (Iizuka and Katz, 2015; Katz and Pietrobelli, 2018). However, innovation in mining diverges from traditional conventions. The discovery of entirely new products is extremely rare, even if product variations are possible (the use of rare earth elements and lithium in green energy applications is an example). Instead, process and organizational innovation is critical and generally aimed at cost reductions (Sanchez and Hartlieb, 2020).<sup>ii</sup> Innovation opportunities arise from both demand and supply, with massive growth in demand from emerging economies and the availability of scientific discoveries, new technologies, and local specificities (Iizuka et al., 2022). In GVCs, user-supplier interactions may also encourage learning and innovation depending on factors such as the governance prevailing, the characteristics of knowledge, and the firm's absorptive capacity (Gereffi et al., 2005; Morrison et al., 2008; Pietrobelli and Rabellotti, 2007). Some authors argue that local outsourcing and learning opportunities increased recently, with large mining houses concentrating on their core capabilities and outsourcing the rest of the activities (Morrison et al., 2012, Fessehaie, 2012). However, existing research shows that hierarchical governance prevailing in mining value chains often constrains suppliers' learning and innovation (Pietrobelli et al., 2023 and 2018). Additionally, social and environmental challenges faced by mining companies also demand innovation (Katz and Pietrobelli, 2018). Yet, despite the evidence of multinational corporations controlling large mining operations and relying on foreign suppliers with hierarchical governance (UNECA, 2013; Molina, 2018; Stubrin, 2017), some evidence of innovative suppliers is also emerging, though not conclusive (Figueiredo and Piana, 2016, 2018; Pietrobelli et al., 2018).

Using patent data, recent examinations of the innovation dynamics in the mining sector reveal positive dynamics, globally and in Latin America since the 2000s (for extensive evidence, see Nenci and Quatraro, 2021). The evidence suggests a sustained growth rate in the mining patent families, guided by pure mining-, exploration- and refining-related technologies. The innovative dynamics followed in Latin America are in line with the overall pattern. Further, in some cases these countries seem to have slightly anticipated the increase in relevance of



mining-related technologies. Indeed, the three focal countries rank among the top five most innovative countries in the Latin American mining sector. Brazil stands out as the most active player in mining technologies. Since 1980, Brazil has contributed to approximately 60% of the total mining patent families in Latin America. The roles of the other two countries are less significant, with Chile accounting for a share below 20% and Peru below 10%, although their contributions kept increasing. Mining exploration and refining technologies are the most relevant mining-technology fields in the knowledge base of Brazil and Chile, with Peru majorly involved in pure mining technologies (such as earth drilling). Interestingly, the increasing rate of mining innovation has been accompanied by a shift toward technological change. Specifically, an increasing weight of environmentally friendly technologies and advanced digital technologies can be observed (Nenci and Quatraro, 2021). These trends also affected Latin America and our focal countries and seem closely intertwined and promising in terms of the expected changes in the extractives sector towards “greener” and modern technologies (IEA, 2021).

### *3.2 GVC-trade patterns in mining*

International trade in raw materials and intermediate inputs has been a prominent feature of world trade flows since ancient times (World Bank, 2020), and with the increasing international fragmentation of production (Feenstra, 1998; Jones and Kierzkowski, 2001), it needs to be analysed through the lenses of GVCs.<sup>iii</sup>

Trade in mining products has some notable features. First, the endowment of mineral resources is a necessary but not sufficient condition for a country to have a comparative advantage in mining products. Complementary inputs are needed to allow a country to export mining products (Tilton, 1983, 1992). Second, trade patterns in mining products are not static, and changes in specialization are possible because of changes in resources, terms of trade, or policy (David and Wright, 1997; Wright and Czelusta, 2004). Third, location-specific geological and technical knowledge can be important in gaining comparative advantages. The case of Latin America confirms this, as it rose as a mining exporter only when the endowments became available for exploitation. This change resulted from a policy change to prioritise the development of the mining sector (Wright and Czelusta, 2007). Finally, mining exporters sometimes naturally move up the development ladder as capital and skilled labour accumulate over time (Davis and Vásquez Cordano, 2013) or when governments implement trade policies to speed up this progression successfully (Anzolin and Pietrobelli, 2021).

Several Latin American countries are important exporters of iron and steel, copper, aluminium and other metals (Nenci and Quatraro, 2021). Brazil has remarkably increased its exports, with iron and steel especially prominent, but has also diversified. Chile experienced the most significant surge in export values over the past decades. Its exports are predominantly concentrated in copper. Peru, too, has a primary specialization in copper but is displaying an emerging positive trend in zinc and tin (Pietrobelli et al., 2023).

Using trade in value-added data, we can observe that most of the value added in mining products is of domestic origin, with a share exceeding the world average. The foreign value-added component is small for all countries and falls below the global average (see Figure A1 in the Appendix). GVC participation is indeed substantial worldwide and for Latin America (see Figure A2) and mainly through forward integration (Korinek, 2020; Nenci and Quatraro, 2021).

Trade in value added can also be used to calculate how much value added each country produces in the mining sector, helping to determine the links between the country and the sector where the value of production originates and the market where it is absorbed in final demand. In terms of production of value added, the country currently producing the highest value added in the mining sector is Chile, followed by Peru and Brazil, all higher than the world average (see Table A1 in the Appendix). In terms of absorption of value added, most of the value added originating in the mining sector in the three countries is absorbed by foreign countries' final demand (see Table A2).

Services are also an essential element of mining GVCs, required for prospecting and exploration, feasibility assessment, exploitation, and closure and remediation. At the world level, beyond the mining sector itself, services are the main input for mining activities. Brazil shows the highest services share, accounting for 33 percent of mining value added, higher than the world average, while the services share is 20 percent for Chile and 15 percent for Peru. The largest providers of traded services to the mining sector of the three Latin American countries are mainly developed economies – such as the US, Netherlands, Japan, and China – casting a negative shadow on the region and its innovation capacity in the sector.

In view of the discussion carried out in this section, the mining sector in the three Latin American countries – i.e., Brazil, Chile and Peru – represents an ideal setting to investigate the relationship between GVCs and innovation and the possible existence of co-evolutionary patterns.

## 4. Data and Methodology

### 4.1 Data

The proposed network analysis relies on two primary data sources: patents and trade in value added.

To measure mining-related technologies, we make use of patent data worldwide. The identification of patent families related to the Mining sector has been carried out by the World Intellectual Property Office (WIPO), which classified Mining patents by exploiting the technological classes indicated in patent documents. The WIPO dataset consists of about 900,000 mining-related patent families over the period 1970-2014. As patents are classified into multiple technology classes, each technology may be related to different economic sectors. To do so, we match technologies, at the CPC 4-digit level,<sup>iv</sup> with the corresponding economic sectors by exploiting the concordance tables provided by Lybbert and Zolas (2014).<sup>v</sup>

To measure GVC trade, we rely on trade data from the OECD TiVA database over the period 1995-2014.<sup>vi</sup> The recent availability of multi-region input-output (MRIO) tables combined with bilateral trade statistics allows us to trace where value is created in the global production chain and hence, which countries and sectors contributed value to it. To this aim, we selected a specific indicator that traces the origin of value added in gross exports. Specifically, it provides estimates of total gross exports by exporting industry  $i$  in country  $c$  broken down by the value added generated by source industry  $h$  in country  $p$ . This indicator reveals how the value of a country's gross exports of intermediate and final products is an accumulation of value generated by many industries in many countries (OECD, 2021).

The identification of Mining-related industrial sectors in the two databases is based on the “Mining and quarrying, non-energy producing products” (D07T08) and “Mining support

service activities” (D09) industry codes with their correspondence to the ISIC Rev. 4 classification (Table A3).

#### 4.2 Networks construction

The construction of the innovative network in the mining sector is based on the co-inventorship criterion, i.e., when two or more inventors collaborate to produce an invention. Since we are interested not only in the co-inventorship relationships between countries but also in the techno-industrial relationships between the co-inventors and the co-assigned industrial sectors, we add a further layer to the construction of the network by taking the country-industry pair as the main unit of analysis. In other words, each node in the *Mining Innovation network* refers to industry  $i$  in country  $c$ , e.g., the “Mining and quarrying, non-energy producing products” in Brazil. Links between country-industry nodes represent co-inventorship relationships in the mining patent families of Brazil, Chile and Peru. To clarify, links identify the co-inventorship relation between the same sector in different countries (when the patent family is assigned to multiple countries of origin but only applies to one industry).<sup>vii</sup> A link is also observed between country-industry nodes when a patent family is assigned to a single country, but it applies to multiple sectors.<sup>viii</sup> Lastly, a link is observed between different countries and different industries when patent families are both assigned to multiple countries and applied to multiple sectors. Moreover, a weight is assigned to each link that is proportional to the number of patent families in which the relationship is observed.

The GVC network is based on how the value of a country’s gross exports of intermediate and final products is an accumulation of value generated by many industries in many countries, and it is directly treated as a weighted directed network whose generic node refers to industry  $i$  in country  $c$ : e.g., the “Mining and quarrying, non-energy producing products” in Brazil. Each directed link between country-industry nodes represents the value-added originating in an industry-country that contributes to the exports of a country-industry. The weight attached to the link represents the value of these value-added flows. To ease the tractability of the GVC network, we have excluded links whose weight is lower than 10% of the trade flows distribution.<sup>ix</sup>

To better capture changes over time in the relatively slow-changing networks dynamics, we divided our samples into 4-year windows and chose to analyze the three temporal waves 1995-1998, 2003-2006 and 2011-2014.<sup>x</sup> Descriptive statistics of the structure of the two networks according to size, cohesion and centralization dimensions are reported in Table A4 in the Appendix.

#### 4.3 Network analysis

There are several dimensions along which the co-evolution dynamics and patterns of the innovation network and the global network of GVC relationships in the mining sector in Brazil, Chile and Peru can be investigated.

A first characterisation concerns the relationship between the *positioning* of the country-industry nodes in the mining innovative network and the GVC network. To do so, we compare the relative rankings of nodes in the two networks over time according to three simple and widely employed network measures, i.e., two centrality indicators, *degree* and *strength centrality*, and the *local clustering coefficient*. As far as the degree of a node is concerned, the number of connections (links) incident on a node is considered such that nodes with a higher

degree are highly connected and considered more central. In our mining innovation network, high (low) degree nodes are industries in countries marked by a large (limited) number of co-invented patents families spanning different industries, either in the same countries or in other countries. In the GVC network, given its directed nature, a sector in a given country is central if it “collects” value added from many (different) sectoral countries (in-degree), “contributes” to the value added of several sectoral countries (out-degree), or both (total degree). Since both our networks are weighted, a similar consideration can be made by considering the strength (or weight) of the network nodes. Such an indicator integrates the information on the number and the weights of links incident to a node by simply calculating their sum: thus, nodes with high strength values are highly central, either because of a large number of connections or more intense connections or both. In the innovation network, this leads to considering the number of patent families involving the same country-industry nodes. In the GVC network, it implies that the monetary value added of a country-industry collected from (in-strength) or contributing to (out-strength) other country-industry gross exports, or both (total strength), is considered in measuring strength centrality. The last measure we consider is transitivity, obtained by computing the local clustering coefficients of the nodes. The clustering coefficient measures the extent to which nodes tend to form closed groups (i.e., closed triangles) with a high density of closed ties (i.e., with the presence of strong neighbours). In general, the most transitive nodes of a network are those with the highest capacity to create local clusters by creating links with the existing connections of a node’s partners.<sup>xi</sup> The comparison of the relative rankings of country-industry nodes in the two networks allows us to identify the reconfiguration of network structures in terms of the appearance of new nodes and the emergence of new central actors, both across the whole networks (degree and strength) and locally (local clustering coefficient). Thus, because of their intuitive and fitting interpretation for the GVC and innovation networks, the chosen measures suit the purposes of our analysis, providing an indication of the *entry* dimension of Schumpeterian patterns.

The second dimension of the analysis investigates the *stability* over time of the relevant centrality rankings and how the rankings of the innovation and the GVC networks co-evolve. Correlation between rankings is computed using Spearman’s rank correlation coefficient applied to all network measures rankings discussed above across the three temporal waves. Intuitively, ranking correlation is associated with the *rank-stability* (turbulence) dimension of Schumpeterian patterns, allowing us to understand the degree to which leading nodes maintain their central role over time.

Lastly, to account for the degree of *concentration* in the network structures, the third dimension of this study investigates sub-graph dynamics and structures by conducting a community detection analysis. Communities are detected when a given group of nodes is densely connected, where the number of connections between the nodes is “greater” than the number of connections the same nodes have with other nodes. Since modularity and similarly derived algorithms are not well-defined for directed graphs and tend to yield unsatisfactory results in weighted ones, we apply the MapEquation algorithm proposed by Rosvall and Bergstrom (2008). Intuitively, the algorithm simulates the behaviour of a random walk through the network. In this way, a community is identified when the random walking takes a long time within the same set of nodes (the community) before moving to another set of nodes. In the GVC network, a community identifies a set of country-industries whose trade relationships are stronger than the relationships such nodes have with other country-industries. Indeed the same community can span national boundaries and involve industries across countries, multi-

industries in a country or both. The same rationale applies to the innovation networks, where a community represents a cluster of country-industries whose co-patenting relationship is more frequent than the patenting collaborations these country-industries have with other industries in other countries.

## 5. Results

### 5.1 Rankings comparison

Figure 1 shows the degree rank comparison in the GVC and innovation network in three time periods (1995-1998 in panel (a), 2003-2006 in panel (b) and 2011-2014 in panel (c)). Each dot represents Brazil, Chile, and Peru's country-industry nodes that take part in both networks (listed on the x-axis). The dotted line identifies whether the country-industry relative position in terms of degree-rank is the same in both networks. The red dots above the line represent the industries of our selected countries for which the degree-based ranking is higher in the GVC network than in the innovation network. Conversely, dots below the horizontal line identify nodes with higher degree rank in the innovation network than in the GVC network. The proximity of country-industries to the dotted line shows the similarity of their degree centrality positioning in both networks.

Overall, the degree centrality ranking of the two networks' structure does not show a significant level of variability at the beginning of the observation period (Figure 1, panel (a)). At the country level, Brazil plays a key role, with most of its industries ranked in both networks. The relative positioning of these industries is similar in both networks, indicating that Brazilian industries in global connections play a comparable role in terms of GVC and innovation networks. However, two notable exceptions are the industries of "Food products, beverages, and tobacco" and, more significantly, "Mining and quarrying (non-energy producing products)", for which their central role is much more relevant in the GVC network. Similar evidence is observable for Chile, where "Mining and quarrying" is one of the best-ranked industries in the GVC network.<sup>xiii</sup>

The centrality role across the two networks becomes more complex (i.e., the entry of more country-industry nodes belonging to all three countries) and heterogeneous (i.e., larger differences in the centrality role between the two networks). During the period 2003-2006 (Figure 1 panel (b)), several Brazilian industries joined both the GVC and innovation networks, resulting in a polarisation of rankings. Most industries in Brazil were among the most connected in either the GVC network or the innovation network. Interestingly, the degree-rank of "Mining and quarrying" is closer to the same-rank line, signalling a relevant gain in centrality for the industry in the innovation network. At the same time, the "Mining support service activities" sector for Brazil enters the networks with a higher rank in the innovation network. Chilean industries followed a similar trend, with "Mining and quarrying" remaining more central in the GVC network. Three Peruvian industries also entered the networks, with "Mining and quarrying" and "Food products, beverages and tobacco" ranking higher in the GVC network and "Basic metals" having a higher relative positioning in the innovation network.

The degree-rank comparison for the most recent period (2011-2014) is reported in Figure 1 panel (c) and shows that the entry of new industries for our countries is still occurring but less pronounced. Brazilian industries gained increasing centrality in the innovation network,

particularly the “Mining support service activities” sector. Chile maintained its better centrality positioning in the GVC network, reflecting the continued high relevance of trade flows. Peru had only one industry present, which was better ranked in the GVC network due to the decreasing innovation activity in mining technologies.

[INSERT FIGURE 1 ABOUT HERE]

Given the importance of considering not only the sheer number of connections but also the intensity of such connections, Figure 2 shows the rank comparison between GVC and innovation networks in terms of link strength. The strength-rank comparison for our countries follows a pattern similar to that observed for the degree. In the first period of observation, 1995-1998, most Brazilian industries ranked similarly in the two networks, except for “Mining and quarrying”, which is more central in the GVC network than in the innovation network. The high entry of Brazilian industries is also confirmed over the period 2003-2006 (Figure 2, panel (b)). Interestingly, when we consider the intensity of connection, both mining sectors are more central in the innovation network for Brazil, indicating that the expansion of innovative activities can be ascribed to a greater extent to the strengthening of relationships with existing collaborating partners. Nevertheless, this higher innovation centrality of the Brazilian “Mining and quarrying” is reverted in the last period of observation, where we observe a better relative position of the sector in the GVC network. “Mining support services activities” remains better ranked in the innovation network. The relative positioning of Chilean industries in terms of strength centrality is in line with the previous evidence and slightly resembles the pattern observed for Brazil. In particular, a higher-ranking position in the innovation network can be observed for the “Mining and quarrying” sector over the period 2003-2006, confirming an expansion of innovation efforts in mining technologies guided by the strengthening of collaboration relationships. Lastly, although there was no innovation activity detected for Peru in mining-related technologies in the first period, the strengthening of innovation collaborations observed for Brazil and Chile between 2003-2006 is also evident in Peru, with all of its industries showing a higher ranking in the innovation network than in the GVC network.

[INSERT FIGURE 2 ABOUT HERE]

Figure 3 presents the comparison of clustering rank in our country-industries between the GVC and innovation networks. This dimension stresses the tendency of nodes to form local clusters of relationships and create close-knit groups. At the beginning of our observation period, a fragmented clustering behaviour appears in Brazil and Chile, with a slightly higher number of industries having better clustering rankings in the innovation network than in the GVC network. The clustering rank of the “Mining and Quarrying” sector in both countries is also higher in the innovation network, showing that, for these two countries, connecting with familiar partners played a greater role in shaping innovation dynamics compared to GVC relationships.

The period 2003-2006 saw a significant shift in clustering dynamics within and between countries. Almost all industries in Brazil showed a growing trend towards forming GVC local clusters, consistent with the idea that the Brazilian mining industry would have stronger linkages with local industries. Meanwhile, Chilean and Peruvian industries tended to cluster more in the innovation network than in the GVC network. Interestingly, the relative importance of clustering in the “Mining and Quarrying” sector was higher in the innovation network for all our countries. During the last observation period (2011-2014), while no marked differences

are observable for Chilean industries, the trend is partly reversed for Brazil, where several industries gained ranking positions in terms of clustering in the innovation network.

[INSERT FIGURE 3 ABOUT HERE]

### 5.2 *Rankings correlations*

Figure 4 shows the Spearman rank correlations matrices for our centrality rankings across waves (degree-based centrality in panel (a), strength-based in panel (b), clustering in panel (c)). In each matrix, rank correlations for the innovation network are in the upper-left triangle, for the GVC network are in the bottom-right triangle, while the bottom-left square reports the cross-rank correlation coefficients between the innovation and the GVC networks, where diagonal values show the rank correlations between the two networks in each temporal wave.

Overall, the GVC network shows stability in the centrality rankings. The ranking correlation is high, especially in terms of degree centrality and strength centrality. This suggests that industries in countries that are leaders in the GVC relationships maintain their role over time. Yet, the ranking correlation between 2003-2006 and 2011-2014 is decreasing, suggesting a slightly decreasing stability in the GVC rankings. Conversely, the innovation network tends to show high levels of instability, as indicated by the low correlation coefficients from the period 1995-1998 to 2003-2006. The increasing technological opportunities in the mining technological field triggered the entry of newcomers/laggards attracted by these new opportunities. This entry, in turn, eroded the technological gap between newcomers and incumbents/leaders, with disruptive effects on the rankings of innovation centrality. However, as mining technological efforts cumulate over time, innovation opportunities and benefits tend to concentrate, favouring incumbents and leading to ranking stability. This dynamic is evident in the degree and the strength measures. Indeed, Figure 4 shows increasing ranking correlations in the innovation networks between the second and the third temporal wave, pointing toward an increase in stability in the centrality rankings.

The clustering-based ranking correlations follow a decreasing stability pattern in both networks, with very low-ranking correlation coefficients for the innovation network and higher, though decreasing, correlation coefficients for the GVC network. The rewiring in the network positioning in terms of clustering behaviour suggests a change in the degree to which country-industries organise their collective innovation and GVC activities around closed groups of relationships. This highlights an increasingly diverging co-evolution pattern characterised, on the one hand, by a strengthening of the newcomers' and widening of the incumbents' innovation relationships and, on the other hand, a change in the fragmentation structure of the GVC-based relationships.

[INSERT FIGURE 4 ABOUT HERE]

### 5.3 *Communities detection*

The analysis of sub-graph dynamics and structures conducted through community detection techniques is reported in Figures 5-6. The colour identifies a specific community. Coloured squares in the legend show which community a given country-sector combination belongs to. The node of interest is always the sector-country combination, but with this visualisation, it is possible to observe whether and to what extent the densest links occur between sectors of different countries or are mostly confined within national borders.

Looking at the GVC network, Figure 5 shows that, in the first period, the mining sector (D07T08) is not part of a single community that affects several countries but belongs to several communities. However, it can also be noted that the mining sectors in Brazil, Chile, and Peru are part of a single community (blue community number 3) which also includes Argentina. This community encompasses most other sectors of these countries as well. This suggests that there is a very high number of GVC-trade connections among the three target countries that affect virtually all sectors of their economies. We can clearly identify a regional network, besides the one involving most European countries (the green one) and the one involving many American and Asian countries (the red one). If few differences are observable in the period 2003-2006, in the last observation period, there is a drastic change with a significant fragmentation of the communities. Except for the communities involving the USA, Mexico, and Canada (historically united in the NAFTA agreement), and China and Taiwan, regional communities practically disappear (see Figure 5 panel (c)).

This is likely a result of the increasing international fragmentation of production and the widespread dispersal of activities that peaked before 2014. The expansion of value chains has resulted in extensive fragmentation within various sectors and a decline of the regional characteristics of value chains.

[INSERT FIGURE 5 ABOUT HERE]

Looking at the innovation network, Figure 6 shows that in the period 1995-1998, the communities' structure was quite fragmented. At the same time, there are some more pervasive communities spanning several industries and countries. This is the case, for example, of the blue community (number 3), the green one (number 2), and partly the red one (number 1). The Mining sector (D07T08) is mostly involved in a few communities spanning countries across the globe. The mining sector of Chile is part of the biggest community (blue) involving most of the mining sectors worldwide, while Brazil's mining industry belongs to the green communities together with Australia, and many European countries, such as the Netherlands and Sweden, among others. The growth in the number of country-industry nodes over the period 2003-2006 led to, on the one hand, the formation of several smaller communities, increasing the total number of identified communities (26). On the other hand, it led to a higher concentration of the mining innovation network communities around the bigger ones (panel (b) of Figure 6). These are mainly composed of related industries of several countries, signalling that the innovation network is increasingly composed and benefits from a strong cross-country collaboration pattern. Such global integration highly engaged the mining industry, particularly Brazil, Chile and Peru, whose innovative activities in the mining sector belong to the same (red) community. The growth in the number of country-industry nodes and the consequent increase in communities' integration is strikingly evident over the period 2011-2014, where most industries and countries joined the biggest community in the mining-related innovation network.

The evolution of the community structures suggests that at the early stage of the development of mining-related technologies, collaborative innovative efforts in the field were mostly confined either within national borders or in tight groups of countries and industries. As the technology entered its early development stage, given the increasing technological opportunities and the prevalence of tacit knowledge at this stage, continued and intense interactions with the sources of knowledge are necessary for the success of innovative efforts. The consequent reduction in the geographical concentration of innovative activities (where



actors expanded in number, scope and localisation of collaborating partners), led to a more globalised organisation of collaborative innovative efforts in mining-related technologies, characterised by the entry of several and more dispersed communities. Once a more advanced development stage is reached, the increasing standardisation of knowledge and the importance of cumulated knowledge and skills led to a strengthening of the mining innovation relationships across countries and industries, resulting in a globalised community.

[INSERT FIGURE 6 ABOUT HERE]

#### *5.4 Evolutionary patterns*

Table 1 offers a schematic representation of our findings summarising the relationship between the different networks' dimensions and the Schumpeterian patterns in the mining innovation and GVC networks over time for our countries, according to the three main indicators, i.e., entry, stability, and concentration. We use the first temporal wave, 1995-1998, as a reference period.

If we look at the innovation dynamics, the 2003-2006 period is characterised by a high level of entry: new country-industries enter the mining innovation network, incumbents expand the number and intensity of their collaborative relationships, and the clustered relationships decrease. Favoured by the increasing opportunities in the mining technological field, these dynamics result in very low stability in the network hierarchy of central innovators. At the same time, ranking turbulence and entry dynamics are associated with the emergence of new and more global communities, decreasing the concentration of mining innovative relationships. Thus, high entry, very-low stability and low concentration are coherent with a widening pattern characterising the mining innovation network in the period 2003-2006. In the third temporal wave, 2011-2014, a deepening pattern emerged. The entry rate decreased, with fewer country-industries joining the network, but the intensity of relationships increased. The centrality rankings stabilized, reflecting the growing importance of knowledge cumulativeness. The globalisation of collaborative efforts in the mining innovation network resulted in fewer but larger communities, leading to a high level of concentration.

The dynamics of the GVC network followed a different pattern. The period from 2003 to 2006 saw a less clear rate of entry, mainly because of an increase in the number of trade relationships. This resulted in very high stability in the ranking positioning of country-industries, showing that leader industries in our countries maintained their central role in the trade network. Concentration was also high during this period, as indicated by the widening of existing global communities. We observed higher entry rates in the last period, with existing trade relationships intensifying through an expansion in the monetary value of such relationships. This expansion was associated with decreasing stability, as the centrality rankings were rewired, altering the gap between leaders and laggards. The intensification of trade relationships and relative instability resulted in a significant fragmentation of global communities and the emergence of new, smaller communities.

[INSERT TABLE 1 ABOUT HERE]

Table 2 illustrates the innovation and GVC patterns for Brazil, Chile, and Peru, providing a closer examination of country-specific patterns along the three crucial dimensions (entry, stability, and concentration). Beginning with Brazil, there is a modest increase in the entry of Brazilian industries during the period of 2003-2006, followed by a reduction in the entry rate during the most recent temporal wave. Conversely, the low-ranking stability of central

Brazilian industries and the low concentration, in line with a widening pattern, are followed by increasing dynamics in the two dimensions, thus configuring a deepening pattern. In contrast, the GVC pattern for Brazil shows quite a different picture. While Brazilian industries strengthened GVC relationships, albeit with modest entry rates, the centrality ranking remained relatively stable, indicating that the leading industries maintained their dominant role. However, concentration is relatively low in the last period of observation, highlighting the emergence of a change in the fragmentation structure of GVC relationships.

Chile's mining technological dynamics are similar to Brazil's, with a high rate of entry in the 2003-2006 wave – configuring a widening pattern –and a deepening pattern in the most recent wave, though with still moderately high concentration and stability. Contrary to the Brazilian case, the strengthening dynamics in the GVC network of Chilean industries and the change in the fragmentation structure have been coupled with low stability in the centrality rankings during 2011-2014, indicating a pronounced rewiring in the leading positions of Chile trade relationships.

Since there is no mining innovation activity in Peru in the first period of observation, patterns in concentration and stability for 2003-2006 cannot be appropriately identified, while, for the same reason, we observe a high entry of Peruvian industries. With respect to 2003-2006, the low entry and the high concentration and stability in 2011-2014 are in line with the other countries' trends. This may show that, despite the late development of mining innovation activity in the country, Peru was able to rapidly benefit from cumulativeness and increasingly codified knowledge in mining technological advancement, participating as a laggard to the overall deepening pattern. The GVC pattern in Peru differed from Brazil and Chile, with a strengthening of GVC relationships associated with low concentration in the 2003-2006 wave but a low entry and stability coupled with a high concentration in the 2011-2014 wave.

[INSERT TABLE 2 ABOUT HERE]

## 6. Conclusions

The paper has investigated the existence of co-evolutionary patterns of knowledge and trade flows in the mining industry for three Latin American countries, combining the Schumpeterian tradition of analysis with social network analysis techniques. The analysis provided a comparison based on the entry, stability and concentration dimensions using three different node-level network measures – degree, strength and clustering –, their rankings, and the community structure.

The results suggest that the mining innovation network and the GVC-trade network present different evolutionary patterns. First, network rankings in the two networks become more complex and heterogeneous over time, with more industries gaining central positions and larger differences in the centrality role between the GVC and innovation networks. The “Mining and quarrying” sector is generally more relevant in the GVC network, although connecting with trusted partners (clustering) played a greater role in shaping innovation dynamics in the sector. Conversely, the “Mining support services activities” tends to show a higher centrality in the innovation network. Second, if we look at the hierarchy of such central positions, the results highlight a decreasing stability pattern in both networks, with a very low ranking correlation for the innovation network and higher, though decreasing, correlation coefficients for the GVC network, suggesting a change in the degree to which country-industries organise their collective innovation and GVC activities around closed groups of relationships. Last, the communities in

the GVC network, also in the mining sector, were fragmented and regional. However, over time, the international fragmentation of production led to a decline in regional characteristics and a drastic change in the community structure. The innovation network showed a more fragmented structure in the early period but, as the number of country-industry nodes grew, the communities became more integrated, especially in the mining sector, leading to a globalised organisation of collaborative, innovative efforts in the field.

Overall, our findings show that the mining innovation network exhibited a widening pattern over time, which is characterised by high entry, low stability, and low concentration. However, during the last years of our sample, we observed a deepening pattern. In contrast, the GVC network showed a different path, with high stability and concentration initially, followed by higher entry rates and lower stability during the last period of observation. These contrasting patterns highlight an increasingly divergent co-evolution pattern, which is characterised, on the one hand, by a widening of the incumbents' innovation relationships and the strengthening of the newcomers' relationships, and on the other hand, by a change in the fragmentation structure of the GVC network. Arguably, despite their position in the GVC network, the growing opportunities in the mining technological field resulted in the expansion of the number and intensity of innovative collaborative relationships for incumbents. Interestingly, our analysis reveals that the increasing importance of cumulativeness along the mining technological lifecycle led to a strengthening of relationship intensity and a stabilisation of rankings, resulting in globalised but concentrated innovative collaborative efforts. It is worth noting that this pattern occurred in a context of concentration and widening of existing global GVC communities, whose expansion in terms of the monetary value of trade was associated with decreasing stability, thus altering the gap between leaders and laggards.

Our analysis also indicates remarkable evolutionary evidence at the country level. The organisation of collaborative mining innovation activities in Brazil closely resembles the aggregate pattern, while the GVC pattern shows a different picture though in line with the overall pattern. The mining technological dynamics of Chile are qualitatively similar, whereas Chilean industries show strengthening dynamics in the GVC network. Peru followed a distinct pattern compared to Brazil and Chile, mainly because of the scant mining innovation activities.

To conclude, this paper contributes to the existing literature by providing novel evidence on the importance of jointly investigating GVCs and innovation dynamics, as well as the need to adopt a dynamic framework to analyse the evolution of networks' structure. Arguably, while these findings advance our knowledge of the evolution of global dynamics in the mining sector in Latin America, it must be considered as an exploratory study calling for further analyses aimed at identifying the main drivers and causal effects, as well as evaluating the impact on a global scale.

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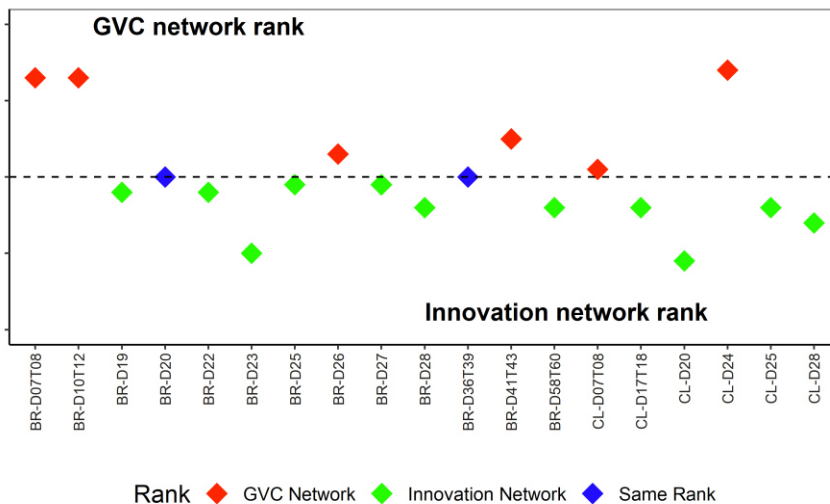
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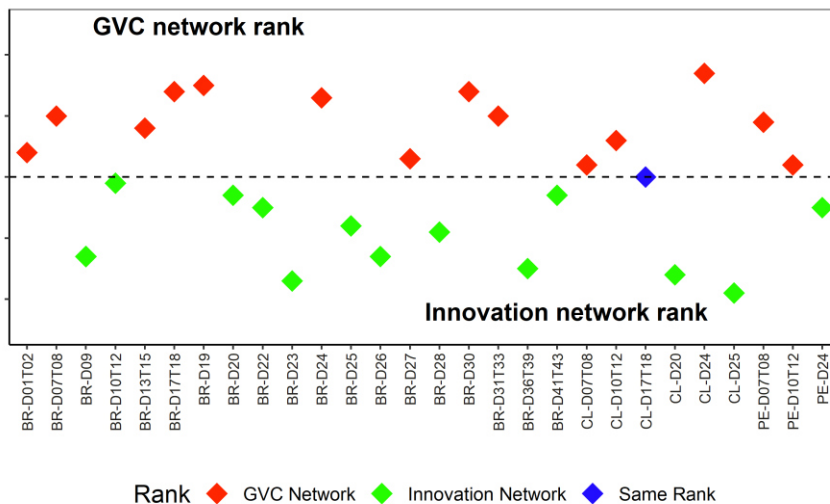
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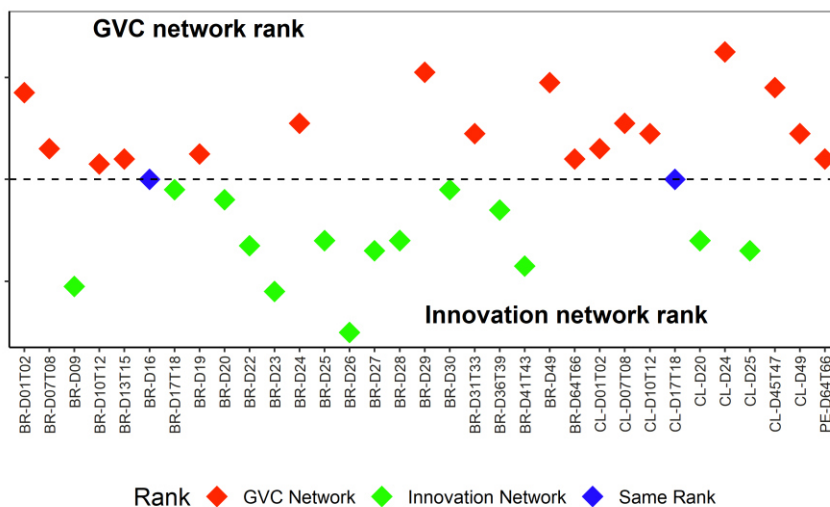
Figure 1. Comparison of the relative degree centrality ranking position of Brazil, Chile and Peru industries across the innovation and GVC network, for each period



(a) 1995-1998

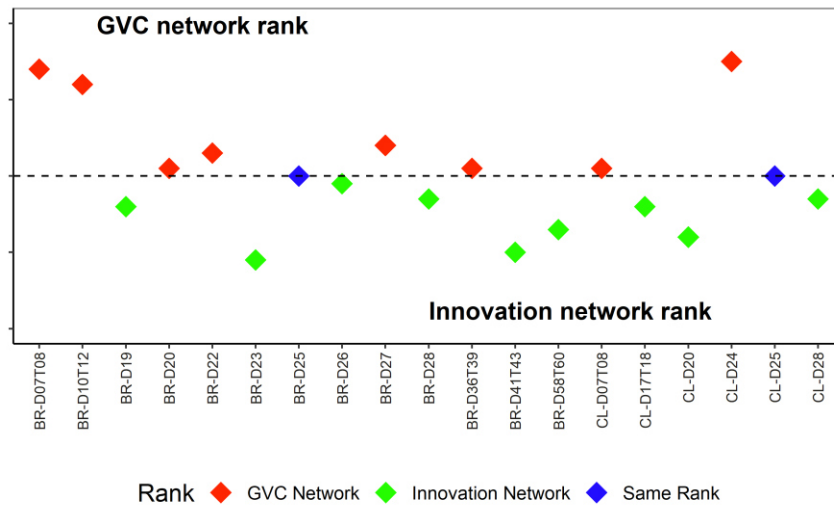


(b) 2003-2006

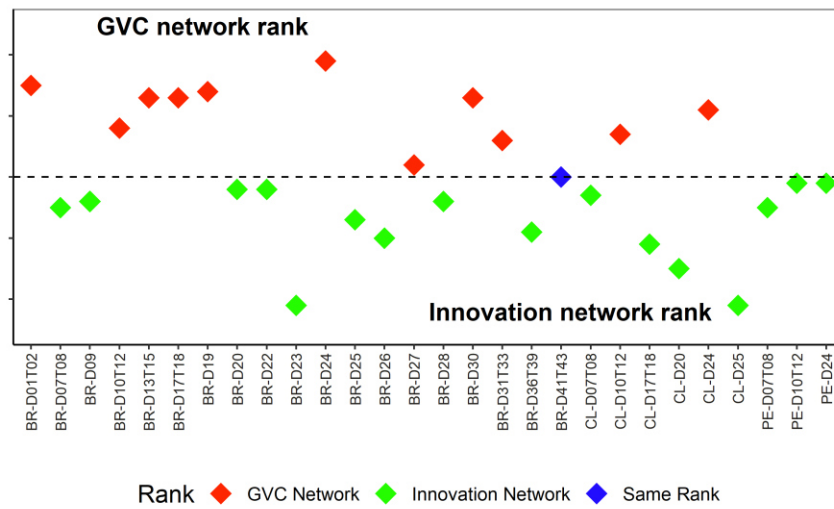


(c) 2011-2014

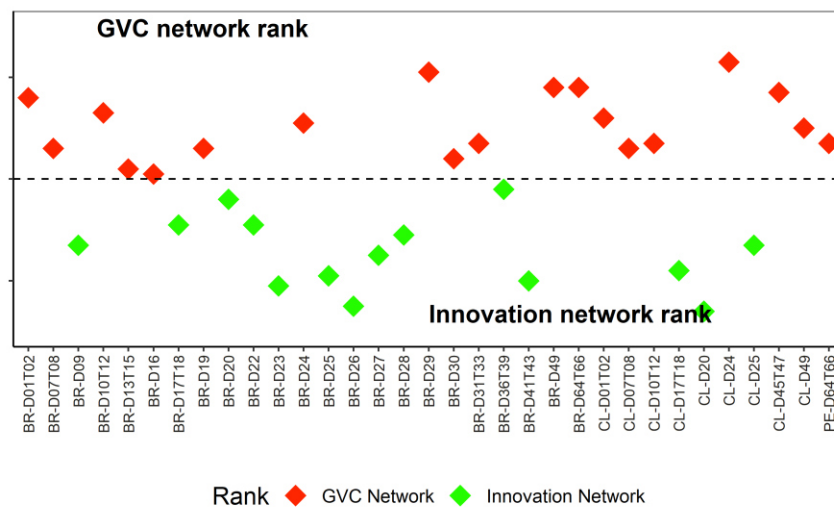
Figure 2. Comparison of the relative strength centrality ranking position of Brazil, Chile and Peru industries across the innovation and GVC network, for each period



(a) 1995-1998

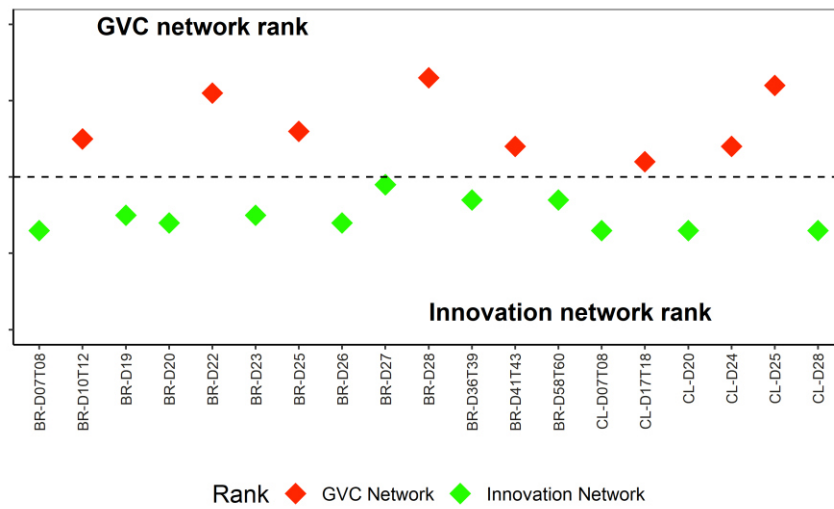


(b) 2003-2006

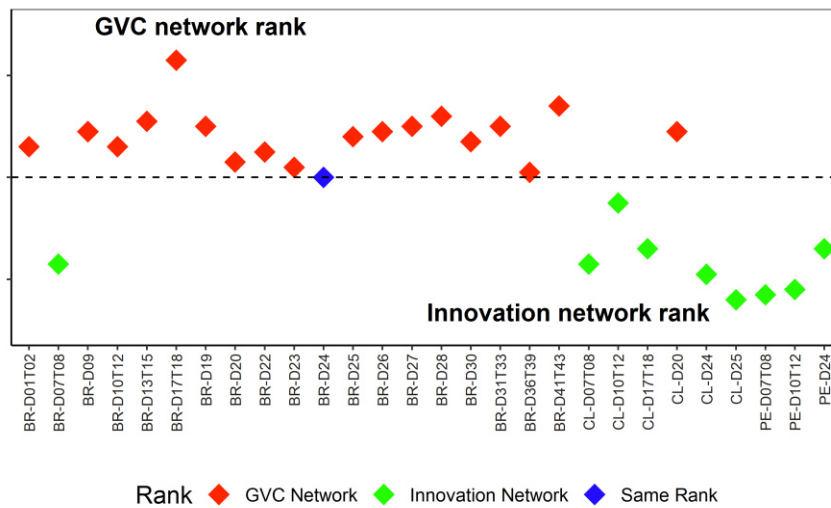


(c) 2011-2014

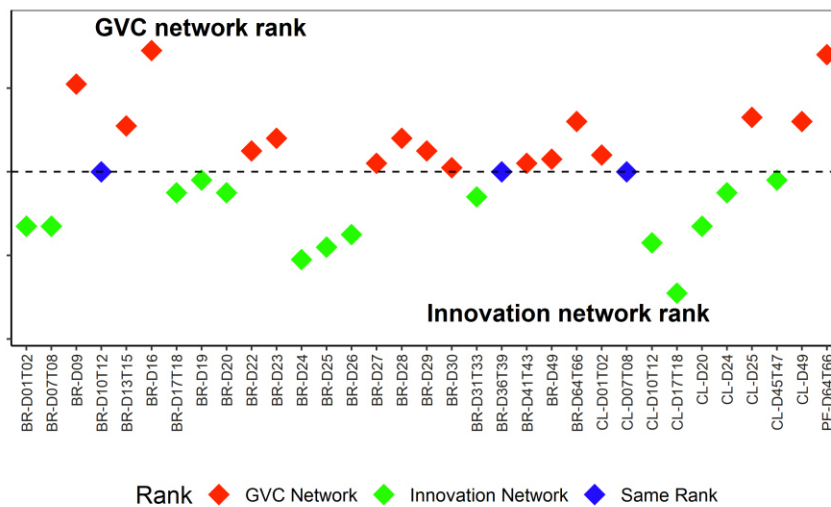
Figure 3. Comparison of the relative clustering ranking position of Brazil, Chile and Peru industries across the innovation and GVC network, for each period



(a) 1995-1998

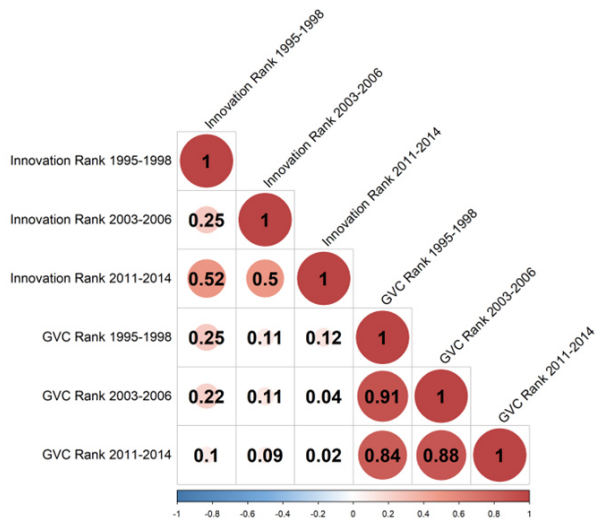


(b) 2003-2006

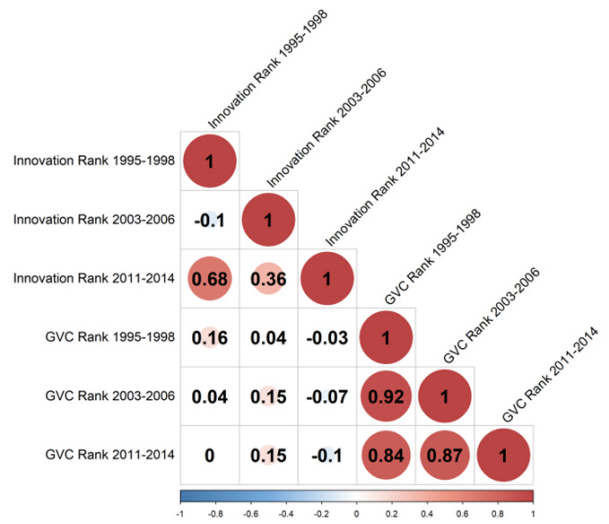


(c) 2011-2014

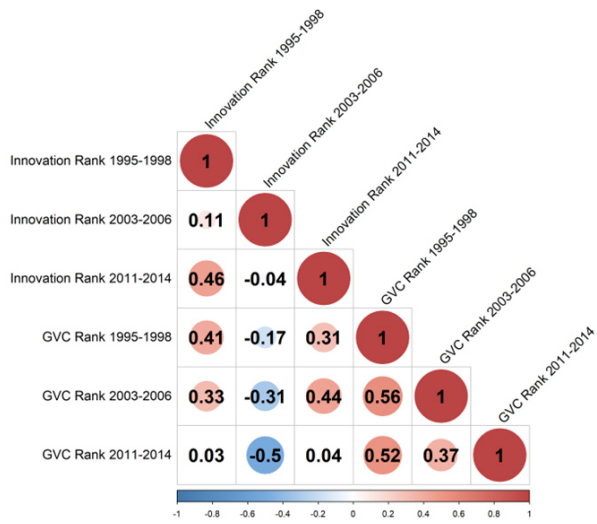
**Figure 4. Rank correlations**



(a) Degree centrality



(b) Strength centrality



(c) Clustering

Figure 5. Communities in the GVC network

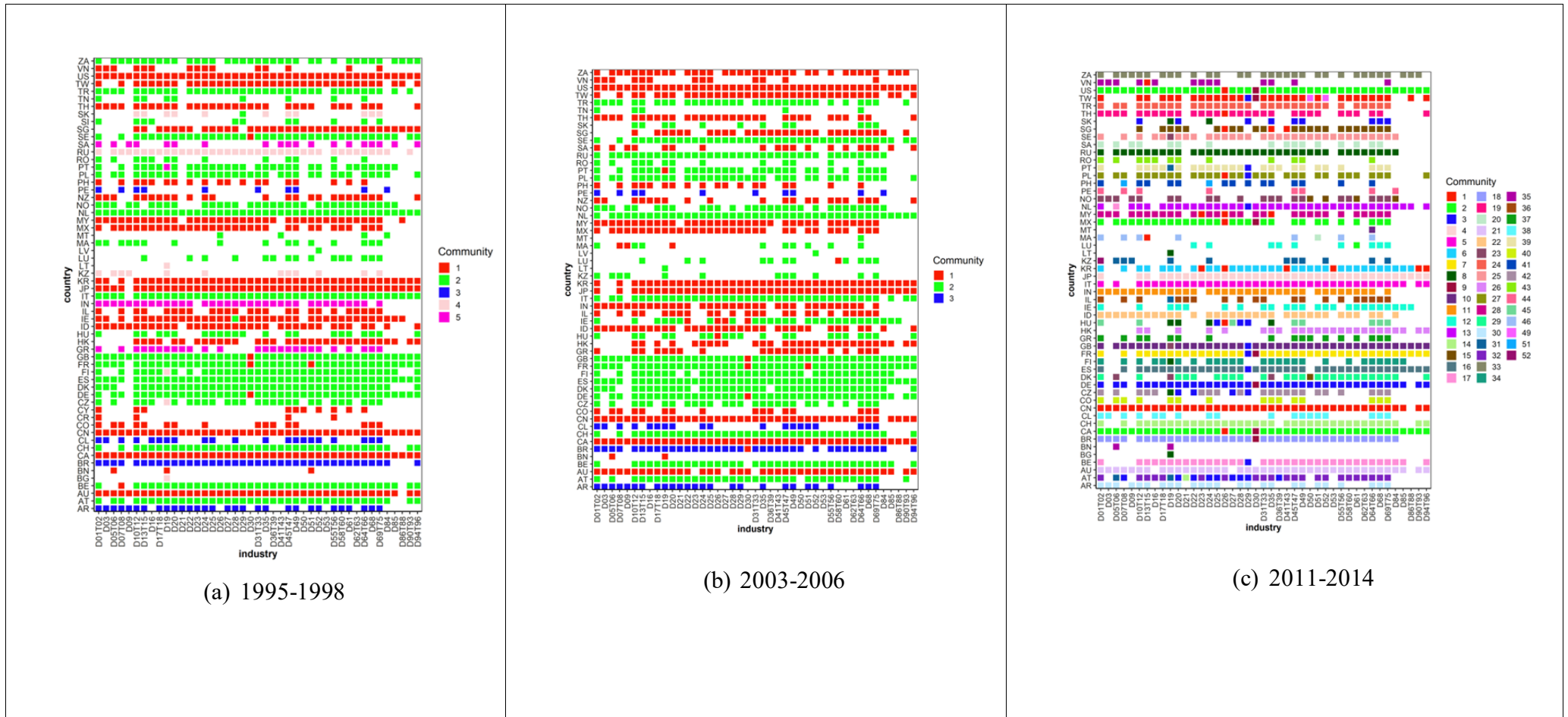
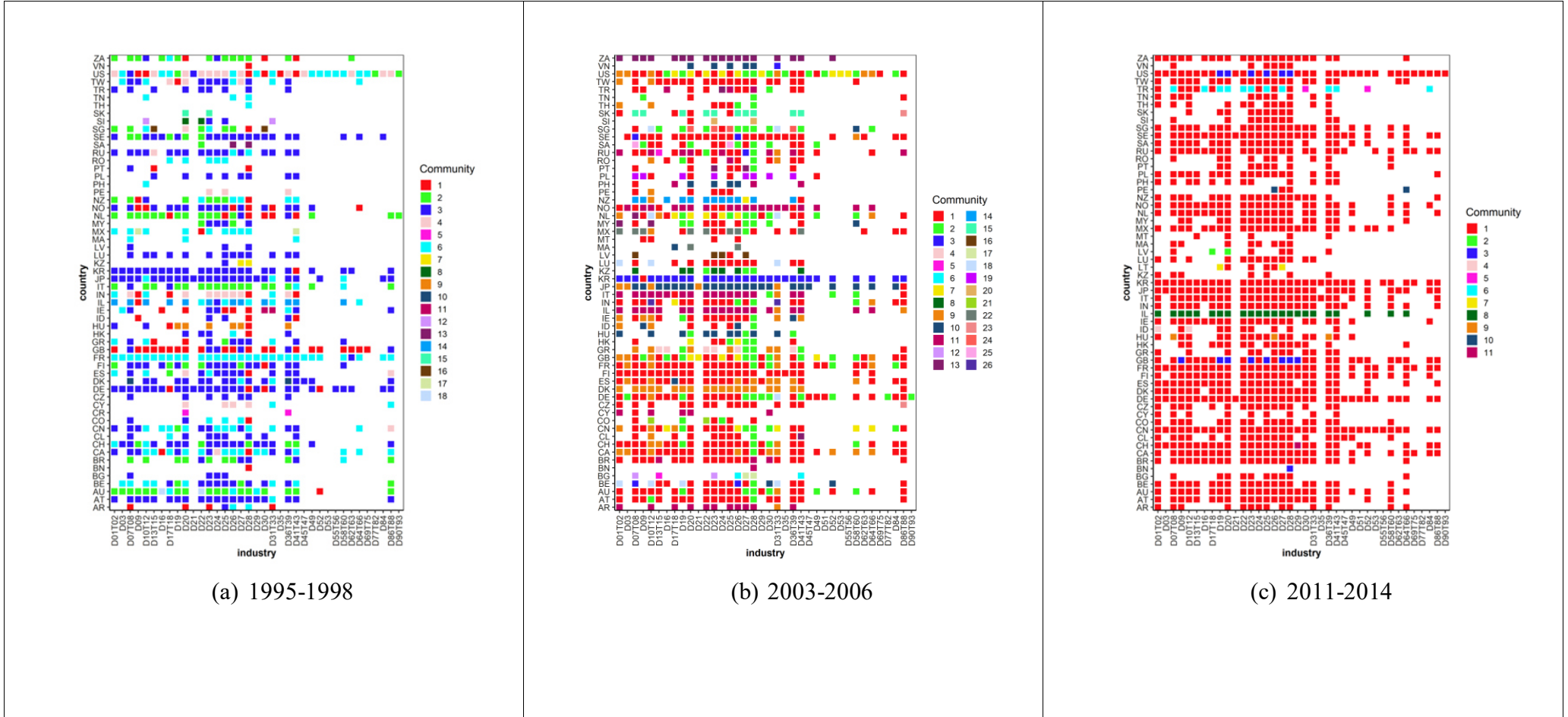


Figure 6. Communities in the Innovation network

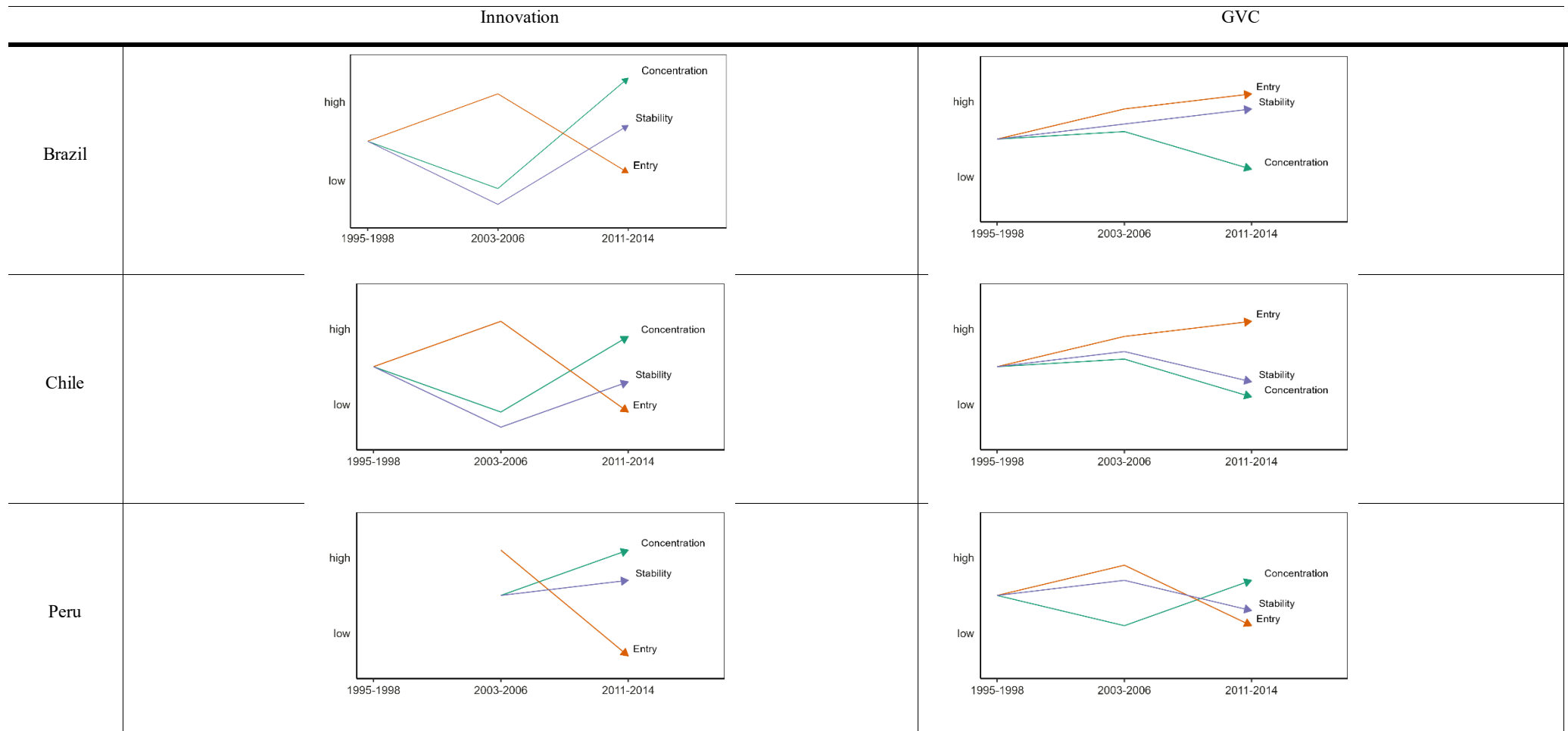


**Table 1. Schumpeterian patterns in mining innovation and GVC network relationships in the three Latin American countries**

Innovation		GVC	
2003-2006	2011-2014	2003-2006	2011-2014
<ul style="list-style-type: none"> <li>• <b>High entry:</b> new country-sector involved in mining innovation network, degree expansion (Figures 1-3)</li> <li>• <b>Very-Low stability:</b> poor ranking correlation, turbulence (Figure 4)</li> <li>• <b>Low concentration:</b> new but wider communities (Figure 6)</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Low entry:</b> less new country-sector involved in mining innovation network (Figures 1-3)</li> <li>• <b>High stability:</b> increasing ranking correlation, stabilisation (Figure 4)</li> <li>• <b>Very-High concentration:</b> decreasing new communities but wider (Figure 6)</li> </ul>	<ul style="list-style-type: none"> <li>• <b>Mid-high entry:</b> new country-sector involved, degree expansion (Figures 1-3)</li> <li>• <b>Very-High stability:</b> strong ranking correlation, stabilisation (Figure 4)</li> <li>• <b>High concentration:</b> less and wider communities (Figure 5)</li> </ul>	<ul style="list-style-type: none"> <li>• <b>High entry:</b> new country-sector involved, strength expansion (Figures 1-3)</li> <li>• <b>Mid-Low stability:</b> decreasing ranking correlation, fragmentation (Figure 4)</li> <li>• <b>Low concentration:</b> less and fragmented communities (Figure 5)</li> </ul>

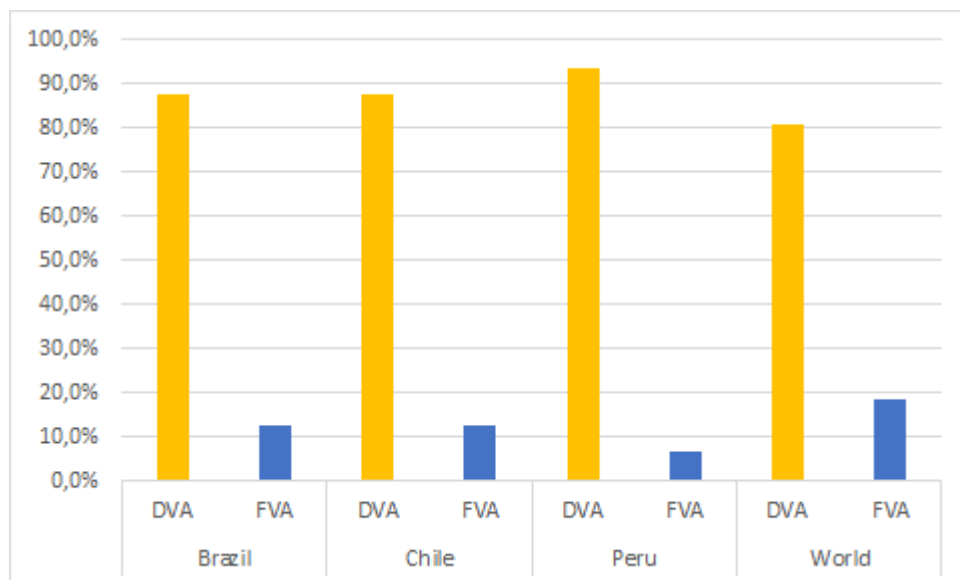


**Table 2. Schumpeterian patterns in mining innovation and GVC network relationships in Brazil, Chile, and Peru**



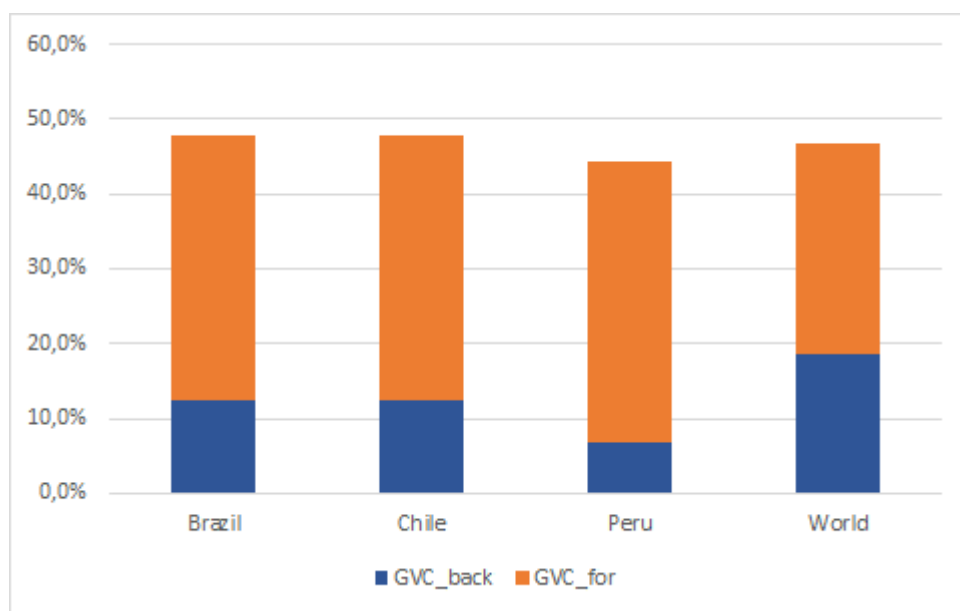
## Appendix A

**Figure A1: Value-Added Components of Gross Exports (2015)**



Source: OECD, Trade in Value Added data (2018).

**Figure A2: Global Value Chain Participation in the Mining Sector (2015)**



Source: OECD, Trade in Value Added data (2018).

**Table A1: Value Added Produced by the Mining Sector, by Country, 2015**

Exporter	Domestic value added (US\$ million)	% of World Value Added
Brazil	12,180	2.25
Chile	21,363	3.95
Peru	14,378	2.66
<i>World</i>	<i>541,472</i>	<i>1.5 (average)</i>

Source: Authors' calculations based on OECD Trade in Value Added data (2018)

**Table A2: Value Added in the Mining Sector Absorbed by Domestic and Foreign Final Demand, by Country, 2015**

	Value added	US\$ million	% of total
<b>Brazil</b>	Absorbed by domestic final demand	16340.63	46.3
	Absorbed by foreign countries' final demand	18949.71	53.7
<b>Chile</b>	Absorbed by domestic final demand	1383.56	12.1
	Absorbed by foreign countries' final demand	10043.04	87.9
<b>Peru</b>	Absorbed by domestic final demand	3507.14	27.5
	Absorbed by foreign countries' final demand	12759.1	72.5

Source: Authors' calculations based on OECD Trade in Value Added data (2021)

**Table A3. Industry list and ISIC Rev. 4 concordance**

N.	Code	Industry description	ISIC Rev.4
1	D01T02	Agriculture, hunting, forestry	01, 02
2	D03	Fishing and aquaculture	03
3	D05T06	Mining and quarrying, energy producing products	05, 06
4	D07T08	Mining and quarrying, non-energy producing products	07, 08
5	D09	Mining support service activities	09
6	D10T12	Food products, beverages and tobacco	10, 11, 12
7	D13T15	Textiles, textile products, leather and footwear	13, 14, 15
8	D16	Wood and products of wood and cork	16
9	D17T18	Paper products and printing	17, 18
10	D19	Coke and refined petroleum products	19
11	D20	Chemical and chemical products	20
12	D21	Pharmaceuticals, medicinal chemical and botanical products	21
13	D22	Rubber and plastics products	22
14	D23	Other non-metallic mineral products	23
15	D24	Basic metals	24
16	D25	Fabricated metal products	25
17	D26	Computer, electronic and optical equipment	26
18	D27	Electrical equipment	27
19	D28	Machinery and equipment, nec	28
20	D29	Motor vehicles, trailers and semi-trailers	29
21	D30	Other transport equipment	30
22	D31T33	Manufacturing nec; repair and installation of machinery and equipment	31, 32, 33
23	D35	Electricity, gas, steam and air conditioning supply	35
24	D36T39	Water supply; sewerage, waste management and remediation activities	36, 37, 38, 39
25	D41T43	Construction	41, 42, 43
26	D45T47	Wholesale and retail trade; repair of motor vehicles	45, 46, 47
27	D49	Land transport and transport via pipelines	49

28	D50	Water transport	50
29	D51	Air transport	51
30	D52	Warehousing and support activities for transportation	52
31	D53	Postal and courier activities	53
32	D55T56	Accommodation and food service activities	55, 56
33	D58T60	Publishing, audiovisual and broadcasting activities	58, 59, 60
34	D61	Telecommunications	61
35	D62T63	IT and other information services	62, 63
36	D64T66	Financial and insurance activities	64, 65, 66
37	D68	Real estate activities	68
38	D69T75	Professional, scientific and technical activities	69 to 75
39	D77T82	Administrative and support services	77 to 82
40	D84	Public administration and defence; compulsory social security	84
41	D85	Education	85
42	D86T88	Human health and social work activities	86, 87, 88
43	D90T93	Arts, entertainment and recreation	90, 91, 92, 93
44	D94T96	Other service activities	94,95, 96
45	D97T98	Activities of households as employers; undifferentiated goods- and services-producing activities	45

Source: <https://www.oecd.org/sti/ind/measuring-trade-in-value-added.html>

**Table A4. Network structural descriptive statistics for the GVC and Innovation networks in each wave.**

	GVC Network			Innovation Network		
	1995-1998	2003-2006	2011-2014	1995-1998	2003-2006	2011-2014
# Nodes	1665	1617	1536	75	131	204
# Links	18522	16993	13751	351	625	1508
Diameter	13	12	13	6	5	4
Average path length	4.166	4.149	4.307	2.602	2.521	2.336
Density	0.007	0.007	0.006	0.126	0.073	0.073
Average degree	22.249	21.018	17.905	9.36	9.542	14.784
Average strength	5562.025	9379.478	17367.025	26908.96	5493.908	25684.765
Clustering coefficient	0.354	0.322	0.305	0.751	0.402	0.367
Degree centralization	0.083	0.077	0.089	0.292	0.38	0.435
Eigen centralization	0.946	0.94	0.955	0.726	0.823	0.815
Betweenness centralization	0.065	0.07	0.095	0.277	0.185	0.178

*Notes:* the number of nodes, the number of links, the diameter and the average path length describe the size dimensions of the two networks. The average path length measures the average shortest distance between any pair of nodes in the network, while the diameter measures the shortest distance between the most distant nodes. Density, average degree and strength, and clustering coefficient describe the cohesion dimension of the network. Density is defined as the normalized ratio between the number of links and the number of possible links. Average degree and strength are, respectively, the average score on degree and strength centrality at the node level. Clustering coefficient is the average ratio of closed triads to the maximum number of possible triads. Lastly, the centralization dimension (the extent to which the networks are dominated, in terms of centrality, by one or a few nodes) is described by the centralization in terms of degree centrality, eigenvector centrality (the degree of a node weighted by the degree of its connections), and betweenness centrality (the number of shortest paths that pass through a given node). All the network statistics are calculated using the *igraph* package implemented in the *R* software environment for statistical computing.

<sup>i</sup> Existing evidence also suggests that in the case of developing countries, one of the main transmission channels through which knowledge and technology spillovers between foreign and domestic firms can occur are supply chain links (Farole and Winkler, 2014; Tajoli and Felice, 2018).

<sup>ii</sup> Process innovation refers to any improvement happening within the mining site, while organizational innovation includes any improvement of operations outside the mine premises. However, several mining innovations will easily fit both definitions (e.g., new exploration methods or new transport systems) (Daly et al., 2022).

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<sup>iii</sup> The decision to locate abroad phases of the production process has significantly affected trade patterns over the last decades, both quantitatively and qualitatively, with the rapid growth of trade in intermediate goods (Antras et al., 2022, Yi, 2003; Baldwin, 2013; Johnson, 2018). This trend has opened the opportunity for small countries with limited capacities or resources to specialize in narrow niches of production, rather than entire sectors, participate in GVCs and benefit from global trade.

<sup>iv</sup> The Cooperative Patent Classification (CPC) is a new patent classification system jointly developed by the European Patent Office (EPO) and United States Patents and Trademark Office (USPTO). The CPC assigns to each patent at least one (usually more) technological class indicating the subject to which the invention relates.

<sup>v</sup> According to Lybbert and Zolas (2014), the technology-sector concordance is constructed using a probability weighting structure, where a weight is assigned for each sector to which a given technology may be related. The concordance is provided at different levels of aggregation for both technologies and sectors. Thus, to uniquely assign technologies to sectors, we first match technology classes at the CPC 4-digits level with the 2-digits International Standard Industry Classification (ISIC) Rev. 4 sectors codes, along with their probability weights. Then, for each technology, we assign the industrial sector associated to the highest value in the probability weight. Following this procedure, we are able to uniquely identify the most relevant economic sector to which a given technology can be related. For the sake of consistency with the GVC network, based on TiVA database, ISIC Rev.4 codes are then aggregated at the TiVA classification level as detailed in Table A3 in the Appendix.

<sup>vi</sup> The TiVA database (2018 release) includes 64 countries and covers 45 industrial sectors, based on the latest System of National Accounts (SNA08) statistics and industrial classification (ISIC Rev. 4). The database is accessible at <https://www.oecd.org/sti/ind/measuring-trade-in-value-added.htm>

<sup>vii</sup> For example, a link between the “Mining and quarrying, non-energy producing products” in the Brazil node and the same Chilean sector node.

<sup>viii</sup> For example, a link between the “Mining and quarrying, non-energy producing products” in Brazil and “Chemical and chemical products” in Brazil”.

<sup>ix</sup> Results are robust to exclusion of the least trade flows value links and are available upon request from the authors.

<sup>x</sup> This time span is the most stable with respect to the evolution of GVCs, avoiding to include the years after 2014 when GVCs experienced a significant slowdown and those of the Covid-19 pandemic, which produced a major shock on GVCs.

<sup>xi</sup> The construction of the two networks is performed through the *igraph* package release developed for the *R* software environment for statistical computing. The three network measures described are computed using the relative functions provided by the *igraph* package. The local clustering coefficient is constructed using the local version of the transitivity function provided in the *igraph* package, which is based on the formula as defined in Barrat et al. (2004) to account for weights in the network links.

<sup>xii</sup> It is worth noting that the absence of industries from Peru is due to the negligible innovation activity related to mining technologies in the country during the period 1995-1998.