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ARTICLE

Rio de Janeiro's insertion in the offshore oil knowledge network

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ABSTRACT

In a context of global production networks, cities are the loci of the knowledge generation process. They bring together various actors and assets necessary for this sophisticated activity. The generation of knowledge involves the interaction between actors within the same city, such as companies, universities, and research centers, and also between actors from different cities, forming a network. However, not all cities can participate in this network, and the literature has mostly focused on networks formed by cities in the Global North and in high-tech industries. This article aims to map and investigate the knowledge network in the offshore oil industry, showing whether cities in oil-rich countries in the Global South are part of this network. The analysis is carried out at the city level, highlighting the cities that appear as important places for generation of knowledge. To meet our goal, we created a patent database using patents granted by the USPTO (United States Patent and Trademark Office) between 2007 and 2017, designed a network based on the inventors' location, and performed the k-core analysis. We found that Rio de Janeiro is the only city in a Global South, resource-rich country that appears in the most central layers of the network. Rio de Janeiro's insertion is based on two groups of actors that play different roles and are highly influenced by the local National Oil Company, Petrobras.

KEYWORDS | Knowledge network; Offshore oil; Patents

1. Introduction

The world economy is increasingly organized in a functionally fragmented and globalized form, in which different actors spread all over the world cooperate with each other in network arrangements. One of the most sophisticated activities in these networks is generation of knowledge. The literature characterized this activity as a cumulative, path-dependent, and interactive phenomenon in which only actors from specific places participate, and the capacity to learn relies heavily on the access to external knowledge and the local absorptive capacity (DAVID, 2000; COHEN; LEVINTHAL, 1990; ACS; ANSELIN; VARGA, 2002).

Researchers have viewed knowledge as a key asset in the context of a globalized knowledge economy, influencing the geographies and organization of production networks in many industries, not only in the traditional knowledge-based ones (PAVITT, 1984; BRIDGE; WOOD, 2006). Even in the oil and gas industry — considered a mature industry with well-established technologies —, the discovery of new reservoirs has posed new challenges regarding the feasibility of exploration, costs, and environmental security. These challenges may require knowledge-intensive activities, based on the adaptation of already existing technologies and on the generation of new knowledge (CRESPI; KATZ; OLIVARI, 2018; SOLHEIM; TVETERAS, 2017).

Cities may be the *loci* of the knowledge generation process because they bring together a wide variety of actors and assets required for such sophisticated activity. Instead of being concentrated within a single firm, generation of knowledge involves the interaction between many actors located in the same city, such as companies, universities, and research centers, and also between different actors from different cities, forming a network (FLORIDA; ADLER; MELLANDER, 2016; LEYDESDORFF *et al.*, 2014; BALLAND *et al.*, 2018). However, not all cities manage to participate in knowledge networks, because this is a highly spatially concentrated activity that follows its own geographical logic; traditional world cities[1]are not necessarily the main nodes in knowledge networks (GOERZEN; ASMUSSEN; NIELSEN, 2013).

Considering these issues, this paper aims to map and investigate the knowledge network in the offshore oil industry, demonstrating whether Global South cities from resource-rich countries are inserted in it. This investigation is relevant because, although oil exploration is geologically conditioned, the same does not occur with generation of

1 Such as the ones studied by Sassen (1991) and Taylor (2001).

knowledge in this industry (PERRONS, 2014; SOLHEIM; TVETERAS, 2017). As the activities related to generation of knowledge are crucial to increase the domestic value added (LEE; SZAPIRO; MAO, 2018) and to capture value in production networks (COE; YEUNG, 2015), understanding the structure of knowledge networks—how different places enter them and which actors are involved—may have implications for the design of public policies that favor such insertion.

To cope with these aims, we created a city-level patent database on the offshore segment of the oil industry, using patents granted by USPTO (United States Patent and Trademark Office) between 2007 and 2017. Based on this database and on inventors' locations, we designed a network. Then, we selected the specific case of Rio de Janeiro to investigate the internal factors that contributed to the city's insertion in the network.

Using network methodology tools, we identified key knowledge-generation cities in an industry typically neglected by other papers, which have continually highlighted traditional high-tech industries, such as biotechnology and electronics (LEYDESDORFF *et al.*, 2014; CASSI; PLUNKET, 2015; NEPELSKI; DE PRATO, 2015; BOSCHMA; HEIMERIKS; BALLAND, 2014; ESLAMI; EBADI; SCHIFFAUEROVA, 2013; BALLAND; SUIRE; VICENTE, 2013). Moreover, our analysis focused on a Global South city, an area which has not been extensively studied in the literature, which has traditionally covered North-American and European cities (BALLAND *et al.*, 2018; BERGE; WANZENBÖCK; SCHERNGELL, 2017; BOSCHMA; BALLAND; KOGLER, 2014; HOEKMAN; FRENKEN; VAN OORT, 2009.

The study of knowledge networks in the most diverse industries and locations is important because, as Lee, Szapiro and Mao (2018) highlighted, generating knowledge is fundamental for upgrading in a context of global production networks. This enables, in the long run, not only to produce and improve value, but mainly to capture it (FRANÇOSO *et al.*, 2020). Many authors studying global production networks and global value chains have treated the economic development resulting from such participation as an automatic process. However, especially in the case of developing countries, mere participation in these networks may not lead to such development, since certain places are trapped within activities of low added value (FRANÇOSO; BREUL; HIRATUKA, 2019).

Similarly, Marin, Navas-Alemán and Perez (2015) highlighted that the participation of resource-rich places in knowledge networks is crucial as it can contribute to the local development of knowledge-intensive activities, helping these places overcome the role of natural resource suppliers and use those resources as a platform to generate knowledge.

This paper is divided into four sections. First, we discuss the generation of knowledge in global production networks. Then, we highlight the specificities involved in the production of knowledge in the oil industry. Next, we present the methods used to develop the proposed analysis. Finally, we discuss and analyze the results.

2. Generation of knowledge in the context of global production networks

Iammarino and McCann (2018) argued that, although in an increasingly globalized context, we face a “concentrated dispersion”: while production is geographically and functionally fragmented, only some places concentrate the highest value-added activities. This spatial concentration is directly proportional to the sophistication and complexity of activities. Hence, as many researchers have already empirically shown — Balland *et al*. (2018), Goerzen, Asmussen and Nielsen (2013), Nepelski and De Prato (2015), Acs, Anselin and Varga (2002), Cassi and Plunket (2015), Li and Phelps (2018) —, generation of knowledge is an extremely concentrated activity. According to Leydesdorf *et al*. (2014) and Balland *et al*. (2018), this concentration has increased in some cities, as some places cluster many research organizations and skilled labor. These places play the role of preferential attachment nodes.

Despite this intense spatial concentration, organizations cannot rely exclusively on the knowledge developed locally. In a globalized context, being part of a network and having the capacity to interact with other places and other actors is crucial. Hence, access to external knowledge is critical to generate knowledge because it enables contact with a more extensive knowledge pool and increases the capacity to adapt to technological changes, avoiding lock-ins (BATHELT; MALMBERG; MASKELL, 2004; GRAF, 2010; BERGE; WANZENBÖCK; SCHERNGELL, 2017). Access to external knowledge takes place via organizations located in the cities, through global pipelines that work as knowledge-transmitting channels (BATHELT; MALMBERG; MASKELL, 2004). This transmission can happen through several mechanisms, such as research cooperation, research and development (R&D) labs, and other means.

To access external knowledge, absorptive capacity is an important asset. According to Cohen and Levinthal (1990), this capacity is related to the fact that the development of internal knowledge depends, inter alia, on the ability to evaluate and use knowledge from an external source. This ability, in turn, is conditioned by prior knowledge already accumulated internally. The ability to absorb knowledge from external sources enables the recognition, assimilation, and proper application of the value of new information.

This external knowledge can spill over and be transmitted to geographically close agents. This happens through the local buzz, which consists in both formal and informal interaction, such as labor mobility and social networks between people and companies (BAHTELT; MALMBERG; MASKELL, 2004; BRESCHI; LISSONI, 2001; BOSCHMA; BALLAND; KOGLER, 2014). The local buzz implies that the connections an organization holds with external agents can also benefit other actors around it, boosting local the generation of knowledge. The role of geographical proximity is not restricted to agents in the same industry, and diversification can contribute to the local buzz (COSTA; GARCIA, 2018). Hence, access to external knowledge is an important step towards the local generation of knowledge.

Although part of the literature has deemed the local buzz fundamental to innovation and generation of knowledge, Asheim, Coenen and Vang (2007) maintained that its importance depends on the knowledge base of each industry. This knowledge base refers to the knowledge dynamics in each area, that is, the combination of tacit and codified knowledge, the possibilities and limits for codification, and the technological challenges involved.

In this view, the oil industry's knowledge base could be classified as synthetic. This implies that technological advances in the field often result from the need to solve certain problems that arise throughout the production process in the interaction between customers (oil companies) and suppliers or specialized service providers. In this base, tacit knowledge is important, as well as the knowledge obtained in other companies and gathered while operating in similar situations. Thus, for industries that have this knowledge base, the geographical proximity and the intense interaction between customers and suppliers or service providers are pivotal.

Although it is possible to classify the oil and gas industry's knowledge base as synthetic, this does not mean that generation of knowledge in the industry follows exclusively the standards defined in this category. As Asheim, Coenen and Vang (2007) argued, industries have characteristics from different knowledge bases, but a predominant category stands out. An example of this variety in the knowledge base of the oil and gas industry is the exploration of the Brazilian pre-salt layer; although offshore exploration requires the adaptation of existing and consolidated technologies, new technologies are also needed.

Knowledge network dynamics have already been extensively investigated in the literature from many perspectives. Some works have focused on the knowledge network of a particular industry; others have focused on specific regions. However, even from different perspectives, most of the studies on knowledge networks have dealt with high-technology industries and/or dynamics in the Global North.

Cassi and Plunket (2015) showed the factors that contribute to scientific and technological collaborations in genomics by investigating the French case. Nepelski and De Prato (2015) analyzed the location dynamics of R&D units in the ICT (Information and Communication Technology) industry. Balland, Suire and Vicente (2013) investigated the geography of innovation and the knowledge networks in navigation satellite systems, focusing on the European case. Eslami, Ebadi and Schiffauerova (2013) used the small world network tool to investigate networks of papers and patents on biotechnology in Canada. Boschma et al. (Heimeriks; Balland and Balland; Kogler) investigated scientific and technological relations in biotechnology and in cities in the United States, respectively.

Restricting the investigation of knowledge networks to high-technology industries naturally excludes some places on the globe, especially in the Global South. Besides, not only high-technology industries are affected by knowledge generation. As Maleki (2013) showed, the oil and gas industry, for example, contradicts the traditional view based on the industry life cycle theory (see UTTERBACK; ABERNATHY, 1975), which states that mature industries tend to be depleted of innovative activities.

3. Knowledge production dynamics in the oil industry

Besides understanding the knowledge generation process itself, it is necessary to understand the special features involved in the generation of knowledge in the oil and gas industry. Although considered a mature industry with well-established technologies (GIELFI *et al.*, 2017), the oil industry has recently been facing changes that severely affected its knowledge and technological dynamics. These changes are mostly related to the difficulties imposed by new reservoirs, located deep into the ocean, and stricter environmental standards (PERRONS, 2014).

According to Bridge and Wood (2006), the generation of new knowledge and the use of new technologies produced mainly by specialized service providers are expanding the exploration frontier, allowing the drilling of reserves in ever-deeper waters and shaping the geography of production. In this context, new and customized solutions are continually required. Since oil wells are located in areas with specific requirements for temperature, pressure, depth, and other geological aspects, the adaptation of existing technologies and the generation of new ones is crucial to allow the exploration of the most diverse wells (CRESPI; KATZ; OLIVARI, 2018; SOLHEIM; TVETERAS, 2017).

Offshore exploration and production (E&P) are the most knowledge-intensive activities in the oil industry. In this segment, innovation projects take around 16 years from the initial concept to commercial application (PERRONS, 2014). International oil companies (IOCs), national oil companies (NOCs), and specialized service providers are involved in these projects. IOCs and NOCs are in charge of E&P projects and demand specific solutions from specialized service providers in different stages of production (SOLHEIM; TVETERAS, 2017), characterizing a strong user-producer relationship (GIELFI *et al.*, 2017).

Perrons (2014) conducted a survey inquiring 199 enterprises in the oil and gas industry and from different countries. His results showed some trends in the oil industry's generation of knowledge. Regarding the actors involved, specialized service providers are currently the companies that most apply for patents in the industry. This is due to the adoption of more collaborative models and the reduction of in-house R&D by oil companies, beginning in the 1990s. In addition, Perrons (2014) also found that universities and public institutions have not been relevant to innovation in the industry, which corresponds to the characteristics of the synthetic knowledge base.

Regarding spatial distribution, Perrons (2014) identified the United States as the center generation of knowledge in the oil industry, especially the Houston area. Other authors, such as Bridge (2008), had already identified this distribution. Despite the spatial concentration, many authors the importance of accessing external knowledge networks in the oil industry, such as McKinnon (2012) and Gielfi *et al.* (2017).

4. Methodology

To comply with the proposed objectives, we adopted a method based on networks and collected, treated patent data. Patent data have a strong relational character, since they link different agents: inventors, organizations, or technologies. Thus, the network-based method is an adequate way to analyze these data.

We developed the methodology in three steps:

1. Formation of a specific patent database;
2. Network design and k-core partitioning;
3. Centrality measures and a specific case analysis.

The first step in the analysis was to select the industry segment. We chose the offshore segment because the exploration phase is knowledge-intensive and has been facing increasing technological challenges for cost reduction, access to ultra-deep wells, and environmental safety, requiring specific technological solutions for each reservoir (BRIDGE, 2008; PERRONS, 2014; SOLHEIM; TVETERAS, 2017).

The option for a specific segment imposed the need to constitute a refined database specifically for it. We collected data on patents and then used the collaboration between inventors to constitute a city-level knowledge network. By placing the cities in a global perspective, we could see how different places are inserted in the offshore oil knowledge network and how this specific network is configured.

One way to explore both the global system and some local factors is through patent data. Although patents are considered a non-ideal indicator, as they do not encompass knowledge generation efforts in an economy as a whole, they are formal outputs of the knowledge generation system (LEYDESFORF *et al.*, 2014), thus providing a clue to track the production of knowledge (BERGE; WANZENBÖCK; SCHERNGELL, 2017).

On the one hand, some authors have argued that patents represent only a part of the R&D performed and do not represent technologies' economic value (ACS; ANSELIN; VARGA, 2002). On the other hand, empirical studies have shown that patents are efficient indicators of innovative activity and are suitable for exploring the location of knowledge production (LEYDESDORF *et al.*, 2014). Specialized service providers in the oil and gas industry have a high propensity to file patents. In oil companies — although they adopt industrial secrecy in some cases —, patenting is also an adopted practice (ACHA, 2002; PERRONS, 2014). These aspects render patents an adequate indicator for the analysis developed in this article.

The first step to conduct the proposed analysis was to constitute a specific database. To do so, we applied the procedures already used by Eslami, Ebadi and Schiffauerova (2013), Murakami (2015), and Bueno (2016). First, we identified the International Patent Classification (IPC) related to the offshore segment. We used the World International Property Organization (WIPO) database, which provides a list of IPCs that match a specific term. To perform this initial search for IPCs, we chose to use very general query terms, such as "subsea+oil", "platform+oil", "underwater+oil", "offshore+oil", and "drilling+subsea". We attained a long list of

IPCs, encompassing different production technologies, and then filtered the results. Next, we checked what kind of technologies these IPCs referred to according to their official definition. Table 1 shows our final list of IPCs.

TABLE 1
IPC list of technologies related to offshore oil exploration

E21B 17/01	E02B 17/02	E21B 15/02	E21B 43/013
E21B 43/01	B63B 21/50	E21B 41/48	E21B 41/04
E21B 21/08	B63B 35/44	E21B 7/104	E21B 41/06
E21B 33/035	B63B 35/58	E21B 19/09	E21B 49/00
E21B 43/12	B63B 21/26	E21B 34/04	E63B 22/02
E21B 33/10	B63B22/02	E21B 33/064	E21B 33/00
E02B 17/00	E21B 7/12	E21B 33/043	E21B 34/06

Source: Produced by the author.

After the identification of suitable IPCs, the next step was to use them to search patents. We used the USPTO database and applied a long timespan, from 2007 to 2017. The USPTO database is widely used in patent studies to avoid potential bias generated by the adoption of an office from a specific Global South country (MIRANDA, 2014). Also, this database has already been used in a patent-based investigation on innovation in the oil and gas industry (MALEKI, 2013).

Although many studies have used patent citation instead of the absolute number of patents as an indicator of knowledge production, this indicator is not the most suitable for a spatial analysis, as Leydesdorf *et al*. (2014) noted. The different number of citations can be due to different practices and regulations, and not exactly to the patents' importance in the network. Hence, analyses based on the number of citations may be biased.

We further refined this initial collection of patents at USPTO by analyzing their abstracts and searching for terms that would allow us to identify the patent as specific to the offshore oil segment. The terms that oriented this refined search were more specific than the ones applied in the IPC search. They were selected based on papers already written about the segment and on the Society of Petroleum Engineers'[2] (SPE International) database, the PetroWiki. After this refinement, we

2 SPE is an international organization with more than 110,000 members in 141 countries, focused on the upstream oil and gas industry (PERRONS, 2014)

obtained a total of 1,217 patents.[3] This sample covered several aspects of the offshore exploration, such as platforms, rigs, injection fluids, manifolds, blowout prevention systems, vessels, pipes, and risers.[4]

After building the database, an undirected network was designed by adopting the city level. To trace the links, we used inventors' location data, not applicant organizations' location. This option was based on the fact that, in many cases, applicant organizations have specific offices to manage intellectual property. However, the location of these offices does not necessarily reflect the location of the R&D laboratories and knowledge production itself. Thus, the inventors' location was used as a proxy for the location of knowledge production, considering that people usually live close to where they work (ESLAMI; EBADI; SCHIFFAUEROVA, 2003). Since people might not always live exactly within a city's boundaries, we adopted a 50 km range to define a city. This means that inventors who live in Katy (US) and Duque de Caxias (BR), for example, were assigned to Houston (US) and Rio de Janeiro (BR), respectively.

After designing the network, we followed some analytical strategies. First, to analyze the global system and its structural and spatial characteristics, we applied the k-core method. Formally, the definition of k-core is "the maximal subgraph H of [a network] G with the property that the minimum number of edges from any vertex in H towards other vertices of H is at least k" (ALVAREZ-HAMELIN *et al.*, 2006). Roughly speaking, the basic premise of this method is that networks can be partitioned in layers, which represent a core-periphery structure according to the characteristics of the network. Therefore, applying this method allows us to identify the central and peripheral nodes in a specific network (CRESCENZI; DATU; IAMMARINO, 2016; ALVAREZ-HAMELIN *et al.*, 2005).

With the initial k-core analysis, we identified the cities in oil-producing countries that occupy the highest hierarchical level of knowledge generation. Two measurements were calculated: the degree centrality, which measures the absolute number of connections a node establishes with another, and the eigenvector. Eigenvector is a key measure in a knowledge network because, as de Nooy (2011, p. 153) stated, "you are more central if you have more contacts—as in the degree centrality—and especially if your contacts are more central, that is, if they have many central contacts." Hence, eigenvector shows the "quality" of the connected places:

3 The patents were grouped by families before composing the final sample.

4 This number is not the universe of patents in offshore oil exploration in the period, but only a sample, due to the limitations of the methodology.

are they central, with a strong position in the network, or are they marginal? Are they a hub in the network, producing and connecting many other nodes? Finally, we chose the specific case of Rio de Janeiro's insertion in the network and investigated it based on the network itself, on other papers, and on official documents.

5. Results and discussion

Our sample comprised 1,217 patents. Patents' inventors came from 377 cities in 30 countries, 10 in the Global South and 20 in the Global North. Many of the characteristics we found were in accordance with Perrons' survey (2014) on innovation in the oil industry. This match indicates that the sample is an accurate picture of the knowledge production dynamics in the offshore segment.

As described in Perrons' survey (2014), universities played a small role in this network, accounting for only 11 patents. Out of these, 7 were filed by Chinese universities. Like in Perrons's results (2014), specialized service providers predominated in our sample: of the 10 main applicants, 7 were specialized service providers and 3 were IOCs.

Another feature was the small number of joint applications of organizations. Only 29 patents were granted for collaboration between two different companies. However, 770 patents involved cooperation between inventors, within the same applicant organization, which can indicate that organizational proximity is very important in this knowledge network.

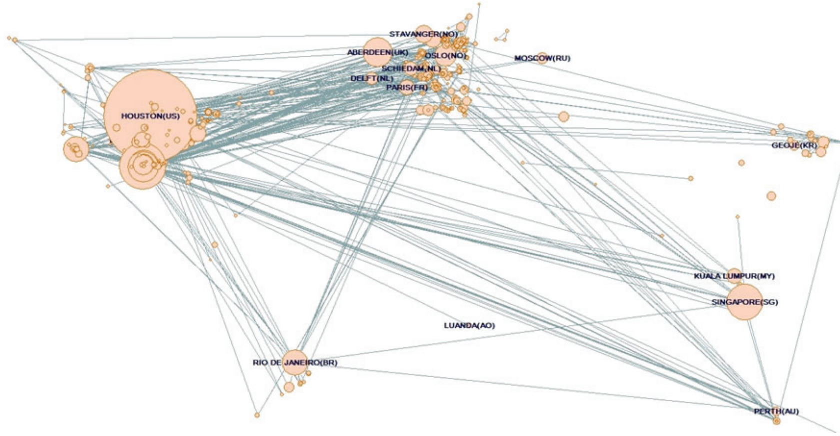
Regarding the places that concentrate knowledge creation in the offshore oil segment, Perrons (2014) found that the United States is a key place. Our data identified the Houston area as the main one. In Europe, knowledge production is less concentrated than in North America. Many nodes in Europe appear as relevant places, such as Oslo, Aberdeen, Delft, Schiedam, and Paris. In the Global South, the highlights are mainly Rio de Janeiro and Singapore[5]. However, Singapore has no oilfield under its jurisdiction, which makes it a resource-poor site.

Figure 1 shows the spatial configuration of the offshore oil knowledge production network and highlights the main cities. The node size was weighted by the degree centrality of each node, that is, it reflects the number of connections that each city holds with other cities through cooperation between inventors[6].

5 Although Kuala Lumpur also appears in the top four layers, the number of patents is still less than half compared to Rio de Janeiro and Singapore.

6 Due to software limitations, node size weighting did not consider loops, but only arcs. However, the k-core partitioning considers both arcs and loops.

FIGURE 1
Offshore oil knowledge network based on inventors' location in patents granted by the USPTO in 2007-2017



Source: Produced by the author based on USPTO data.

A first analysis of the global knowledge network of the offshore oil segment revealed structural characteristics. This network has a density of 0.014, showing that only 1.4% of all the possible connections have been made. This reveals that, although many nodes participate in the network, many of them are not strongly connected to others. The average degree is 9.92, which means that each city is, on average, making 9 connections.

The network is composed of 2,178 arcs and 1,377 loops. Loops are connections a node establishes with itself. Therefore, the number of connections between different cities is only 1.5 times higher than the number of connections a city holds with itself, evidencing that both connections between inventors located in different cities and the ones between inventors in the same city are important in this network.

Applying the k-core algorithm, the network was partitioned in 8 layers, from the most peripheral to the most central layer. Although the network was composed of 377 cities, only 15 were part of the two most central layers. This indicates a high concentration. Though many cities participated in the knowledge flows, these flows had a clear hierarchy, and only few cities were in the core, as displayed in Table 2.

TABLE 2
Innermost layers of the k-core partitioning of the offshore oil knowledge network based on inventors' location in patents granted by the USPTO in 2007–2017

<table>
<tr><th>City</th><th>Layer</th><th>City</th><th>Layer</th></tr>
<tr><td>Aberdeen (UK)</td><td rowspan="11">8</td><td rowspan="2">Magnolia (US)</td><td rowspan="11">7</td></tr>
<tr><td>Paris (FR)</td></tr>
<tr><td>Cambridge (UK)</td><td rowspan="3">Montgomery (US)</td></tr>
<tr><td>Oslo (NO)</td></tr>
<tr><td>Edmonton (CA)</td></tr>
<tr><td>Houston (US)</td><td rowspan="3">Richmond (US)</td></tr>
<tr><td>Yokohama (JP)</td></tr>
<tr><td>Missouri City (US)</td></tr>
<tr><td>Bergen (NO)</td><td rowspan="3">Rio De Janeiro (BR)</td></tr>
<tr><td>Singapore (SG)</td></tr>
<tr><td>Perth (AU)</td></tr>
</table>

Source: Built by the author.

According to the k-core partitioning, Rio de Janeiro appears as the only city in an oil-rich country in the Global South that has managed to enter the offshore oil knowledge network at a global level and in the highest positions. Thus, the subsequent analysis will concentrate on Rio de Janeiro.

5.1 Rio de Janeiro in the offshore oil knowledge network

In this section, we spotlight Rio de Janeiro's participation in the network, showing the characteristics, implications, and main actors that contribute to this unique insertion. All topics discussed in this section reflect the characteristics of the database we built.

The main applicant for patents with inventors located in Rio de Janeiro is the local NOC, Petrobras, which accounted for approximately 50% of the patents in which Rio de Janeiro was involved. The other 50% were divided among 10 international companies, mostly specialized service providers. Petrobras's patents originate from inventors in Rio de Janeiro, representing many of the loops happening inside the city. The flows between Rio de Janeiro and other cities are established through research cooperation in foreign companies, mainly special service providers.

Besides the local NOC, there is no other national organization generating knowledge on an international scale. Considering the new format outlined by the oil industry, in which companies providing specialized services are increasingly the main source of innovation, the city of Rio de Janeiro does not have a strong national representative in this segment, depending upon foreign companies to generate knowledge in specialized service provision.

The data showed two groups of actors with specific functions regarding Rio de Janeiro's insertion in the offshore knowledge network. First, there is Petrobras, which is the main responsible for the loops, contributing to the internal generation of knowledge through local connections. Second, there are foreign companies, mainly specialized service providers, which are responsible for the arcs by providing access to external knowledge and connecting inventors in different cities.

Rio de Janeiro is the inventors' location of 26 patents in the database. Other Brazilian cities were present in only 4 patents, which shows the strong concentration of offshore oil knowledge generation related in this city. Out of those 26 patents, 12 involved the cooperation with inventors located in other cities. This cooperation is shown through Rio de Janeiro's degree centrality. The degree of 42 accounts for the number of interactions established with other places.

Rio de Janeiro's main international cooperator is Houston. This means the Brazilian city is strongly connected to the hub of the network, having access to the center of knowledge generation on offshore oil. This is due to the strong participation of foreign companies in Rio de Janeiro's knowledge flows, since many of the companies that develop research in Rio de Janeiro also have R&D facilities in Houston. However, Rio de Janeiro is also connected to many less central cities, which generates an eigenvector of 0.0178, a relatively small number[7].

Considering the k-core partitioning, Rio de Janeiro is in a strategic position, as it is part of the second innermost layer. This position has implications for maintaining the city's participation in the network, since sparsely connected nodes, such as those in the peripheral layers, are more likely to be excluded from the network (KHAOUID *et al.*, 2015). In addition, nodes in the most peripheral layers have less access to external knowledge, as they are weakly connected to other nodes. Consequently, they are more likely to be locked-in and to have more difficulties in upgrading inside the global production network (CRESCENZI; DATU; IAMMARINO, 2016).

The cities in the innermost layers, such as Rio de Janeiro, are more tightly connected to the network and involved in more cooperation projects with other cities (Alvarez-Hamelin *et al.*, 2005). This core position entails more access to

7 In this network, the eigenvector ranges from 0 to 0.6.

external knowledge. Hence, Rio de Janeiro's position in the network is more stable compared to that of more peripheral cities. Also, in the most central layers, Rio de Janeiro is more exposed to non-redundant knowledge, which in turn contributes to reinforce its central position in the network and sustains an upgrading trajectory in the global production network.

According to the database, Rio de Janeiro's external flows rely heavily on foreign specialized firms. The installation of these companies' R&D units in Rio de Janeiro is strongly related to the nature of the knowledge base of the oil industry, as discussed in previous sections. Two main factors may explain this behavior: the technological requirements of the pre-salt layer and Petrobras's expertise in deep-water exploration.

As previously mentioned, the specific technological requirements of the pre-salt layer and the synthetic knowledge base of the oil industry—strongly based on a user-producer interaction—lead several suppliers and specialized service providers to set up in Rio de Janeiro. In doing so, they aim to facilitate interaction with oil companies that lead E&P projects and to provide solutions that meet the specific technological challenges posed by the pre-salt oil reserves.

Piquet, Hasenclever and Shimoda (2016) showed that, of the 18 new oil and gas R&D centers that have been installed in Brazil since 2006 — when the pre-salt layer was discovered — 15 are located in Rio de Janeiro. Among the companies that installed R&D centers in the city are Baker Hughes, FMC Corporation, and Vallourec. The installation of foreign R&D facilities boosted significantly the local generation of knowledge because foreign companies not only contributed to their practices, routines, and technologies, but also develop new knowledge. R&D facilities also boosted the access to external knowledge, as many new technologies and adaptations started to involve the cooperation between researchers in Brazilian and in overseas facilities.

Rocha and Urraca-Ruiz (2011) interviewed some of the specialized service companies that installed R&D facilities in Rio de Janeiro. When inquired about their motivation for installing R&D units in the city, the companies said their goal was to meet the technological demands of the pre-salt layer, and their solutions served as a basis for other deep-water oilfields. Some of the companies also said they wanted to learn from Petrobras, which developed expertise in the exploration of deep-water oilfields.

Therefore, Petrobras plays a double role in the insertion of Rio de Janeiro in the network. It directly contributes to the generation of internal knowledge and, at the same time, attracts foreign companies, which decide to install R&D units in the city. This shows that Petrobras is a key player in explaining Rio de Janeiro's insertion in the offshore oil knowledge network.

6. Final remarks

The article aimed to map and analyze the knowledge network in the offshore oil segment, showing which cities in oil-rich countries in the Global South are inserted in the network. We used patent data as a proxy for the production of knowledge and employed tools of the network methodology. This analysis was motivated not only by the gaps in the literature but also by the fact that, especially in the productive networks of natural resources, the production of knowledge is crucial to upgrade the network and enable greater value capture. Rio de Janeiro was the only city that met the requirements of belonging to the Global South and to an oil-rich country. It was present in the higher layers of the network.

When analyzing more deeply the characteristics of Rio de Janeiro's insertion, we found that Petrobras is a key actor in the production of knowledge internally, accounting for the majority of loops within Rio de Janeiro. However, with regard to access to external knowledge, Petrobras contributes only indirectly. The Brazilian NOC attracts R&D units from foreign specialized service companies, as Rocha and Urraca-Ruiz (2011) already mentioned. For that reason, the connections between Rio de Janeiro and other cities have been traced through patents granted to foreign specialized service companies, which shows that the city still relies heavily on foreign capital to access external knowledge.

Our analysis placed Rio de Janeiro in a prominent position at a global level when compared to other cities in the Global South. This position cannot be understood without referring to the history of efforts by Petrobras to build local skills and knowledge since the 1970s. These efforts are in line with recent studies that have related the upgrading capacity within production networks to the structuring of a national innovation system that supports this process (LEE; SZAPIRO; MAO, 2018). Thus, understanding Rio de Janeiro's position in the network necessarily involves the nature of the knowledge base of the oil industry and the role played by both national and international organizations that initiated research cooperation in the area.

Finally, this article raises questions that can be explored further in future works. In line with Lee, Szapiro and Mao (2018), the relationship between the type of participation of different cities in production networks and the constitution of a local innovation system can be explored, addressing how this dynamics works and in which industries this relationship can be observed.

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