

Maleki, Ali; Rosiello, Alessandro

Conference Paper

Which countries benefit most from emerging technological opportunities?

54th Congress of the European Regional Science Association: "Regional development & globalisation: Best practices", 26-29 August 2014, St. Petersburg, Russia

Provided in Cooperation with:

European Regional Science Association (ERSA)

Suggested Citation: Maleki, Ali; Rosiello, Alessandro (2014) : Which countries benefit most from emerging technological opportunities?, 54th Congress of the European Regional Science Association: "Regional development & globalisation: Best practices", 26-29 August 2014, St. Petersburg, Russia, European Regional Science Association (ERSA), Louvain-la-Neuve

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Which countries benefit most from emerging technological opportunities? An enquiry into the changing geography of knowledge base complexity in the upstream petroleum industry

1. Introduction

In this article we explore the possible implications of the evolution of knowledge base complexity at sectoral level for international geographical patterns of innovation and catch-up processes. The literature on sectoral innovation systems has proposed hypothetical relationships between different dimensions of technological regimes and geography of innovation since the early developments of the research agenda. When the knowledge base of a sector is characterized by tacitness, complexity and systemic features, the innovative activities tend to be geographically concentrated. The same argument is suggested in the conditions of high technological opportunities, high appropriability and high cumulateness. In contrast, when there is low technological opportunities, low appropriability and low cumulateness, innovative activities tend to be geographically dispersed (Malerba and Orsenigo, 1997; Breschi, and Malerba, 2000). However, these relationships has rarely been empirically studied (Breschi, 2000 is an exception at sub-national level not at international level). Explicit analysis of the *dynamics* and evolution of this relationship over time is even scarcer, although some studies in the geography of innovation has marginally touched upon this issue (Such as: Vertova, 2002, Ernst, 2005b)

The present research is interested in investigating the extent to which the knowledge base characteristics may conditions the possibility of late comer countries to enter and catch-up in the realm of innovation. We ask here whether there is a possibility of catch-up within the upstream petroleum industry and how may it depend of the technological complexity in the sector. The question of catch-up and change in geographical patterns of innovation should be seen as two different sides of the same coin, because if there is no process of catching-up or falling behind, there is no change in geographical patterns of innovation. Therefore, there is a high level of geographical persistency signalling lack of catch-up processes. On the other hand, if geographical patterns of innovation change, there should be some shifts in the relative position of each country and lack of persistency. The main players which contribute to stability or change in geographical patterns of innovation are not countries as territories, but companies and perhaps other non-firm innovators which operate within certain national boundaries. Nonetheless, the issue must be addressed from a national perspective in order to understand which features of national systems of innovation and/or macro-economic trend impede or stimulate the emergence of new innovative agents, and/or their geographic relocation.

A changing geography can be attributed attributed to various factors operating at different levels. These include broad global trends such as firms' internationalization and liberalization of markets

(Athreye and Cantwell, 2007), national specific factors like size and quality of demand (Cantwell, 1995), or supportive national systems of innovation (Vertova, 2002). Sectoral and technology specific factors in terms of technological regimes such as complexity or appropriability are another set of important factors (Lee and Lim, 2001; Vertova, 2002, Ernst, 2005b, Sorenson et al., 2006). We are particularly interested in this last element, i.e. knowledge base complexity. This is because there is a tendency in economic geography to explore contextual and institutional factors affecting innovation, while the nature of knowledge and its increasing complexity is under researched.

This article is organized in 6 sections. After introduction, section 2 employs the literature on the geography of complexity to propose some clarifications and formulate research hypothesis. Section 3 explains data collection and examines the dynamics of knowledge base complexity in the upstream petroleum industry in. The dynamics of international geography of innovation in the upstream petroleum industry is addressed in section 4 followed by the analysis of its relationship with the changing dominant type of knowledge base complexity in section 5 where we conclude.

2. On the geography of knowledge base complexity

One of the earliest contributions concerning the link between complexity and geography of innovation is perhaps Patel and Pavitt's (1991) argument on 'non- globalization' of innovative activities. They argued that geographical concentration enables companies to cope with complexity in innovation processes. Later, Pavitt (1999) emphasised the role of both *cognitive* and *organizational* complexity in geographical concentration of innovative activities. He argued that the *cognitive* complexity of a system which is "made of numerous components and subsystems whose interaction are often non-linear and therefore impossible to predict" requires geographical concentration in order to facilitate coordination and exchange of tacit knowledge (Pavitt, 1999; P. X). Similarly, *organisational complexity* which in his definition implies mobilization of "wide and increasing range of fields of specialized knowledge", could create strong incentives for geographical concentration to facilitate linkage between knowledge communities and learning processes (Pavitt, 1999; P. X).

Similarly, Breschi (2000) argued that the more tacit, complex and part of a larger system is the knowledge base, the more geographically concentrated is the innovation process, and vice versa. More recently Sorenson (2005) argued that complexity of knowledge, in the form of highly interacting pieces, leads to higher geographical concentration of industries, because complexity puts serious constraints on knowledge flows. His empirical evidence suggests that 10-15% of the variation in the geographical concentration of the industries can be explained by an average measure of knowledge base complexity. In other words, the higher the knowledge complexity, the more geographically concentrated is the sector.

However, Ernst (2005) documented a paradoxical case. In spite of increasing extraordinary cognitive and organizational complexity, the cheap design industry actually experienced geographical *decentralization*. Ernst (2005) asks whether “it possible to exchange complex knowledge, even if innovation agents are located at distant locations?” (p. 51). His answer is that cognitive proximity through global innovation networks (GIN) is a suitable organizational solution to these particular kinds of complexities. But what makes this solution possible in the first place is the possibility of some degree of modularity which facilitates outsourcing specialized work to distant suppliers. Outsourcing and related geographical relocation of innovative activities are driven by three forces (i), specialization which facilitates knowledge growth at the level of components and modules; (ii) lower costs, if activities are relocated to cheaper countries; and (iii) local customization according to the peculiarities of demand in each location.

Given the possibility of modularity, it seems that Ernst(2005) refers to a different kind of complexity where an increasing range of specialized knowledge from a *decomposable* knowledge base of the industry. Since the knowledge base of the industry is relatively decomposable to relatively independent components, it is possible for specialized agents to innovate at the level of components without necessarily having access to other bits of knowledge of the system. Given this different view to the complexity where modularity strategy is applicable, market and semi-market decentralized systems could serve the coordination function. Therefore, vertically integrated coordination structures may not be needed to facilitate cross-border knowledge exchange. We refer to this type as *breadth* complexity, where the variety or breadth of knowledge system is increasing without necessarily intensive interaction between different knowledge domains.

However in the presence of systemic complexity the situation is very different. When the degree of interdependency is high, changes in one component of the knowledge system (Saviotti 2011) could have radical and unpredictable impacts on other components. . As a result, access to systemic or architectural knowledge is required and it can be very difficult for distant players to cooperate and innovate. Diffusion of knowledge with systemic complexity over long distances is very challenging and requires recipients with high absorptive capacities in (Sorenson et al., 2006; Sorenson, 2005).

From this distinction, we can conclude that a sector is relatively more open to innovators from other geographical domains when breadth complexity is increasing and systemic complexity is decreasing. In contrast, coping with increasing systemic complexity is more challenging for distant agents. Therefore, we formulate the following research hypothesis:

H: When breadth complexity increases and systemic complexity decreases, we expect to observe relatively more rapid geographical dispersion and wider catch-up opportunities. In contrast, we expect slower geographical dispersion or even a move to more concentration, with more limited catch-up experience when systemic complexity increases.

3. Towards data collection and the dynamics of knowledge base complexity

The upstream petroleum industry is key for the analysis of the dynamics of technological complexity in the resource base industries (Yin, 2003). A glance at the drivers of change in the sector illustrates the structural transformation of the sector both in terms of technological opportunities and complexity of the knowledge base. This industry exemplifies several phases of transformation and reconfiguration, providing a very relevant setting for the analysis of dynamics of technological regimes and geographical patterns of innovation (Maleki, 2013).

In order to examine our hypothesis with regard to the case of upstream petroleum industry, we use Derwent Innovating Index, the patent database which classifies all upstream petroleum industry patents in class H01. This class covers exploration, drilling, well services and stimulations, production and their sub segments of the upstream petroleum industry. In order to avoid double counting, we rely on the records of Derwent patent families which group similar inventions registered in different territories. Patent counts are used as a proxy to capture of dynamics of innovative performance of the sector.

Patent data is the only rigorously classified information about technological innovation covering both long time periods and a wide range of countries. The advantages and limitations of patent data for the analysis of innovative activities is a widely discussed issue in the literature, while Maleki and Rosiello (2014) provide an in-depth account of the main disadvantages in relation to the empirical analysis presented in this paper and how they have been tackled.

Following Fai(2007), we use patenting growth rate to capture dynamics of technological opportunities in upstream petroleum industry.

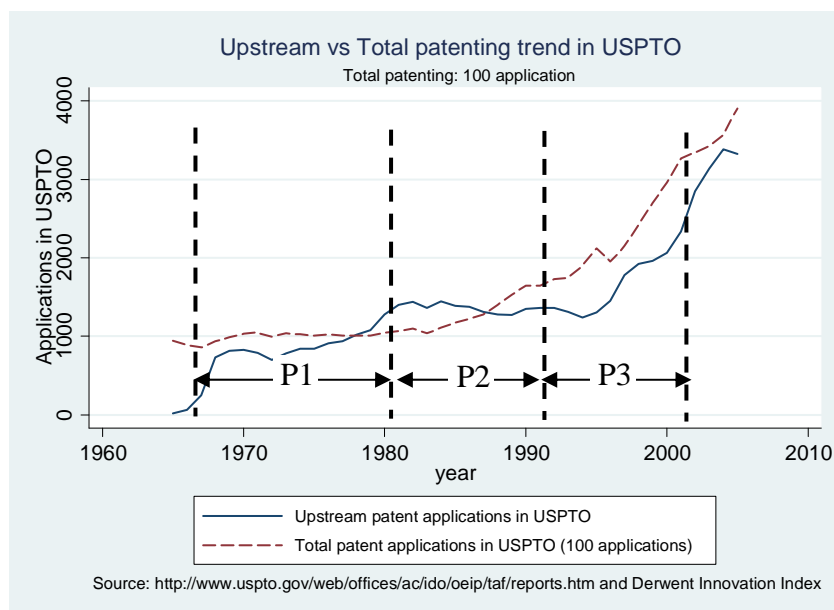
Figure 1 presents the innovation trend in the upstream petroleum industry according to the number of patent applications in the US Patent Office (solid line). The dash-line shows the trend of total patenting in USPTO at 1% scale to control for the changes in the overall level of patenting. That is to examine whether observed dynamics of innovation is a reflection of overall patenting behaviour at global level, or the result of internal mechanisms within the upstream petroleum industry. According to figure 1, the dynamics of innovation in upstream petroleum industry presents three distinct periods over the last four decades. From the early 1970s until the mid-1980s, we observe a growing trend where the number of US patent applications in upstream petroleum industry almost doubled while the total patent applications is relatively constant (p1). The second period runs from mid-1980s to mid-1995s, with a negative trend in technological opportunities in the sector, while the total patenting is growing in the posit direction (p2). Third period begins from mid 1990s when innovation grows very rapidly both totally and in upstream petroleum industry (p3). Therefore, we observe that the upstream petroleum industries experienced two periods of high technological opportunities (p1 & p3) and a period of low innovation rate (p1) between these two periods when the oil prices was low

and the industry is stagnating.¹ This picture is not compatible with the standard industry life cycle model, whereby mature industries develop limited innovation capacity, whereas the upstream petroleum industry moves from a stagnation status in p2 to a very innovative era in p3 with high technological opportunities (Maleki and Rosiello, 2014).

We ask therefore: *which countries are able to capture the benefits of these emerging opportunities and what is the role knowledge base complexity in this regards?*

To answer this question requires a clear distinction between the two types of knowledge base complexity identified in the section 2.

Figure 1 The number of US patent applications over time



3.1. Breadth complexity

According to Wang and Tunzelman (2000) breadth complexity refers to the range or scope of different subjects, fields or elements in a system. More recently, other authors refer to the concept of technological *variety*, (Frenken et al., 2007; Krafft and Quatraro, 2011) referring to distribution of things or elements within different categories. This application of the term has recently become popular in both economics of innovation (for example Boschma and Iammarino, 2009; Neffke et al., 2011).

In this research, we focus on the dynamics of *variety* to describe the evolution of breadth complexity. *Variety* has been considered an important aspect of sectoral knowledge base in previous studies (Krafft et al., 2009 and 2011), providing a basis for inter-sectoral comparisons. Following recent research on the dynamics of sectoral knowledge bases (Krafft et al., 2009 and 2011), we employ the

¹ For a detailed analysis of driving forces behind these dynamics see (Maleki, 2013).

Entropy index to measure variety as a proxy for breadth complexity. This index measures the degree of disorder or randomness in a distribution where more balanced distributions get higher values.

For formal notification, variety is drawn from the entropy index formula:

$$V = \sum_{g=1}^G P_g \ln \left(\frac{1}{P_g} \right) \quad \text{Where : } P_g \text{ is the share of patent in 4-digit classes.} \quad (1)$$

3.2. Systemic complexity

The main concern of scholars writing on systemic complexity (Wang and von Tunzelmann, 2000; Antonelli, 2011) is the volume of interdependencies and degree of interaction between elements of a system. For example Patel and Pavitt (1997) implicitly take this view and Sorenson and Rivkin (2006) directly refer to this dimension of complexity. This specific notion of knowledge complexity is present when “the opportunities to generate new knowledge are conditional on the identification and integration of the diverse bits of complementary knowledge that are inputs into the knowledge production process” (Antonelli, 2003, p.507).

The complementarity between bits of knowledge is the source of recombination and creation of this type of complexity. Knowledge indivisibility is the outcome of this process where systemic knowledge serves new functions which are not achievable by individual bits of knowledge. In sectors with high levels of this type of complexity, effective production and competitiveness requires access and control of a diverse range of knowledge on the one hand, and integrative coordination capability on the other. Successful innovation is not possible without full understanding of the compatibilities and complementarities of diverse ranges of technologies (Antonelli, 2003). Because the source of this complexity is often *systemic innovation* (Chesbrough and Teece, 1996), we label this type of complexity as *systemic complexity*.

Proxies to measure complexity should consider the links and interactions between different elements of the knowledge base and capture the recombinant nature of knowledge and its endogenous systemic complexity. In order to measure systemic complexity, the network representation of the knowledge base is very relevant. According to this view (Saviotti, 2009, 2011), the knowledge base has a co-relational structure comprised of nodes and links between these nodes. In this view, nodes are technology classes and links represent relationships between technologies connecting nodes together. The measure of systemic complexity should consider the connectivity and the relationships between technologies or the structure of relationships between different knowledge domains. The dynamics of complexity are understood from changes in the pattern and strength of linkages and interactions between the nodes (Maleki and Rosiello, 2014).

Social Network Analysis (SNA) has a powerful toolbox to characterize the connectivity of the network. A matrix of co-occurrence of technological classes is formed to represent the knowledge

network where the value of each cell is the number of inventions that two technological classes appeared together (Krafft et al., 2011). In other words, the more two technologies are jointed, the higher their connectivity.

In order to create a measure of connectivity at the level of a network, we rely on the *average of the degree centrality of all nodes of the network*. However, following (Krafft, 2011), we used the *average* measure of *degree centrality*, weighted by relative frequency. This takes into account the highly unequal strength of the nodes, giving higher weights to important technological classes. Accordingly, the measure of systemic complexity of the knowledge base is *weighted average degree centrality (WADC)*, as follows:

$$WADC = \sum_n [NDC_n * (P_n / \sum_n P_n)] \quad (2)$$

When the speed of formation new nodes outweighs the formation of links, the network becomes less connected and systemic complexity decreases (WADC decreases). In contrast, when the formation of new links is stronger than appearance of new nodes in the knowledge network, network connectively increases (Saviotti, 2011), signalling the rise of systemic complexity (WADC increases).

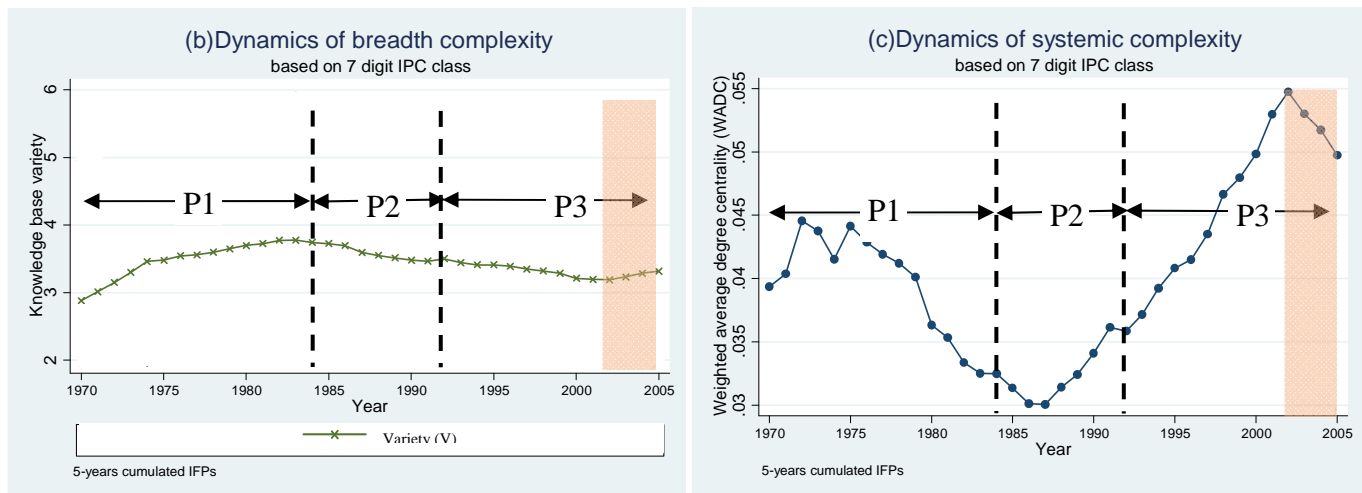
3.3. The dynamics of knowledge base complexity in upstream petroleum industry

The dynamics of both types of knowledge base complexity in the upstream petroleum industry are presented in figure 2. The trends of breadth and systemic complexity in figure 2 (b) & (c) present two major stages. The two types of complexity seem related, yet moving in opposite directions, with a transitional period in early p2. Breadth complexity expresses an upward trend over p1. After achieving their peaks in early p2, it turns to a downward trend over p3. In contrast, systemic complexity has an overall declining trend over p1 which turns to an upward trend over p3, after it hits its bottom in early p2. Looking at the knowledge base as a complex system represented by a knowledge network, we know that breadth represents the nodes, while systemic complexity represent the links and the connectivity of the network.

The first period is considered as the period of high instability and uncertainly, because of increasing technological variety in the sector. Not only do new technological classes emerge and are added to the knowledge base of the industry, the industry moves towards more equal distribution of innovation within different technological classes. This pushes up technological variety, moving the sector towards higher breadth complexity.

The dynamics of knowledge base complexity in the upstream petroleum industry are also presented in figure 2 using the *WADC* measure. The trend of systemic complexity over most of p1 takes a downward trend. . As suggested by Saviotti (2011), it is driven by higher rate of creation of new nodes (or new technological classes), compared to new links between new and existing nodes (or the relationship between different technologies).

Figure 2: Dynamics of the breadth and systemic complexity of the knowledge base in the upstream petroleum industry



Historically, this is the period of rapid technological progress in the sector, we many current available technologies (like 3-D seismic and horizontal drilling) are first introduced to the sector. When new promising technological fields are explored, it takes some time for the innovators to understand the complementarity and the relationships between new and existing knowledge domains. We expect the emergence of novelty first to create new but poorly connected nodes, and therefore temporarily reduce the connectivity of the knowledge network (Saviotti, 2011). The first period in upstream petroleum industry is the manifestation of this proposition. Emergence of new but poorly connected nodes increases the technological variety of the knowledge base, while also reducing its connectivity and total level of systemic complexity.

As predicted by the knowledge network theory (Saviotti, 2011), the situation began to change when the direction of systemic complexity reversed in the beginning of p2 in 1986, implying the rise of connectivity of the knowledge network. This increasing trend continued almost by the end of p3. The diffusion and establishment of new technological fields explored in p1 contributes to explain the changing overall pattern in p3, when the rate of creation of new links overtakes the rate of emergence of new nodes. It does not imply that the emergence of new technological domains stopped; however their relative size became negligible compared to the established technological fields. By the end of p1 and during p2, the most promising fields which involve the highest technological opportunities gradually become known to industry participants. Historically, this time is when integrated service companies gradually emerged. As it was difficult for operators to manage the increasing range of specialized sub-contractors in in different technical domains and coordinate the interfaces, integrated service companies took this role. The aim was introduce total and integrated solutions combing different related technologies in unified packages (Barreau, 2002; Chafcouloff, 1995).

When the processes of systemic complexity are dominant, the knowledge base of the industry is not developed just by accumulation of knowledge in existing knowledge domains or simple addition of new technical domains to existing ones, but through interactions and recombinations between existing and new technologies.

As a result of this strong emergent complementariness, the knowledge base of the sector is not easily divisible or decomposable and systemic complexity becomes increasingly high. The high complementarity and systemic complexity increases investment returns on innovation, yet it increases barriers to entry for latecomers. “As far as knowledge complexity is concerned, it is clear that the larger the number of the bits of knowledge that can be recombined, the larger is the chances of generating new relevant knowledge” (Antonelli, 2003 p. 598). However, the dominance of systemic complexity after early p2 introduces important challenges and implications for latecomers. It is by definition more to the advantage of those who possesses or have access to the knowledge components, and against those who miss one or more of the critical components.

The post 2002 decline in WADC seems odd, but still compatible with our theoretical argument. The patterns looks like a technological discontinuity whereby the speed of new links in the knowledge network falls behind new nodes and therefore the knowledge connectivity decline. We did not find a real structural explanation for that, but we think it is a consequence of nature of data wherein information about links comes with more delay in the data set compared to the information about the nodes.

4. Dynamics of international geography of innovation in upstream petroleum industry

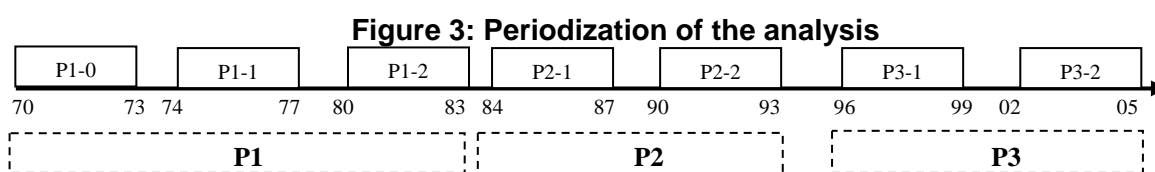
Before examining the geography of the changing patterns of innovation in upstream petroleum, it is important to explain how geographical data have been used. For international comparisons, the inventor’s country (IC) is often seen as the most relevant entry in geographical studies (OECD, 2009). Nonetheless, in the case of catch-up countries this assumption may be misleading. This is because these data do not distinguish between innovations performed by domestic or by foreign companies in a country.

For the purpose of this paper, we need to identify the original country of the innovator companies, regardless of the location of invention itself. But, this information is not available directly in our database. In order to tackle this issue in the data, we need to know who owns the innovations and where their original countries are. Since, inventive activities of foreign affiliates in other countries are often attributed to the host country if the affiliates are registered officially as a local company, we introduce and use the concept of *assignee’s main invention country* (AMIC). This concept assumes that the original country of each assignee company is the country where the majority of its inventions are located. For example, the majority of BP’s inventive activities are located in the UK, although it also has some inventive activities in other countries such as US or Norway. In other words, we

consider the number of patents owned by the companies of that country (captured by the concept of AMIC), regardless of the location of their innovative activities. We are confident that using this approach could reasonably guide us to find the original countries of the innovators companies. This is because that, it is very unlikely that the volume of innovative activities of one company be greater in a single foreign country than its home country.

We analyse the evolution of geographical concentration of innovation in different countries and the number of innovating countries over time in order to explore the changing geography of innovative activities. According to these measures, we can examine the hypothesis of this research with regard to possibility and extent of catch-up processes in different periods and answer the research question.

We explore changing geographical patterns of innovation from the beginning to the end of the three main periods where we observe considerable changes in the nature of technological regimes. This is because, we do not expect knowledge related changes in geographical patterns in short times. In order to smooth the trends and ignore the short term fluctuations, our measures are drawn from data collapsed within 4 years of the beginning and the end of the main periods, as shown in the figure 3. The length of the first period is 14 years, but the length of both the second and third periods are 10 years. Therefore, p1 is divided into one introductory sub-period (p1-0) and two other sub- periods (p1-1, p1-2). This means that all three main periods cover 10 years with two 4-year sub periods at both sides and a two year gap in the middle, leaving out the introductory sub-period of p1-0.



4.1. International geographical concentration of innovative activities

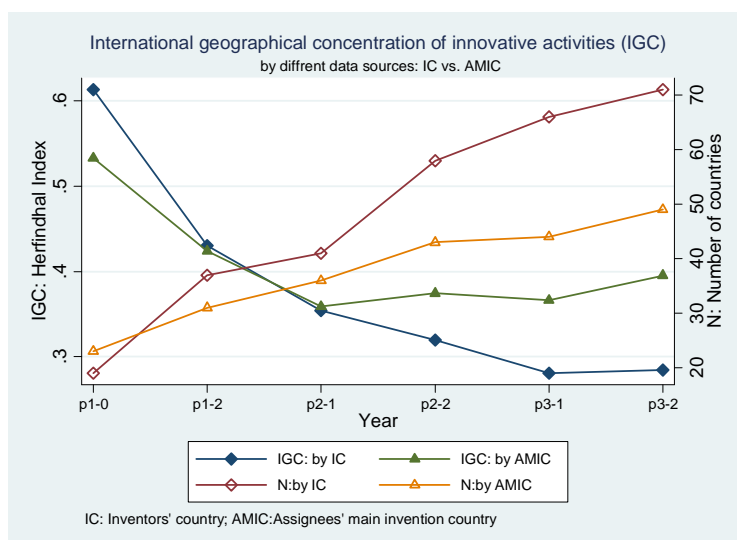
The dynamics of international geographical concentration (IGC) of innovation across different countries are presented in figure 4 based on the Herfindahl index, using both IC and AMIC sources (left axis). In addition, the number of contributing countries (N) is presented on the right axis. It shows that the number of countries both in terms of the location (IC) and ownership (AMIC) of innovation has increased over time. Except in early periods, the number of owner countries (AMIC) has always been less than the number of countries where innovative activities are located. Moreover, the gap has increased for most of the observed period, particularly after early p2. This means that the speed of entrance to new countries as the location of innovations is more than the speed of entrance of new owner countries.

The comparative analysis of geographical concentration is even more informative. The comparative trend based on IC and AMIC shows that in the earliest periods (from p1-0 to p2-1) concentration

based on both sources experienced a similar downward trend and stayed close to each other. This means that some new centres of innovation emerged in new countries where most of innovations are also owned by local companies. As a result, the concentration index according to both sources (IC and AMIC) followed pretty similar patterns. However, they began to diverge after the period p2-1, largely because of an overall gradual upward trend of concentration of the ownership (AMIC) location of innovations. Concentration according to inventor location (IC) continued its downward trend, though less speedily up to p3 when its downward trend stopped.

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Figure 4 International geographical concentration of innovative activities (IGC)



Dominance of the knowledge base’s systemic complexity during p2 works against dispersion of innovative activities and increases concentration to facilitate exchange and coordination of complex knowledge flows. These findings support the idea that to manage and coordinate complex knowledge bases, cognitive and organizational proximity between different divisions and/or subsidiaries of the same company (although geographically distributed), is more important than spatial proximity. As a result, innovations become more concentrated in terms of ownership throughout p3, while also being more geographically dispersed in terms of the physical location of innovation. This conclusion is in

line with the strand of research which distinguishes between the role of geographic, organisational and cognitive proximity in managing complex knowledge bases (Breschi and Lissoni, 2001; Boschma, 2005; Lagendijk and Lorentzen, 2007).

4.2. Technological catch-up

In spite of high entry barriers for companies from new countries, some countries may have managed a higher than average growth rate over a long enough period, which allowed them to reduce the gap with leading countries. We define these as catch-up countries. In this section we explore whether there are such countries and how they emerged?

We use a Galtonian regression model to explore them and their emerging trajectory. The Galtonian regression model was originally suggested by Hart and Paris (1956) in economics and also employed by Dalum and Laursen (1996) for the analysis of trade specialization. This method is suggested to explore the convergence vs. divergence among different objects under study based on distribution patterns of one variable at two different points of time. The aim is to understand whether our units of analysis are becoming more similar (convergence) or dissimilar (divergence) in terms of a variable under study (such as size). As a result, it is applied to explore catch-up in innovative activities in this study. If catch-up processes are effective, statistically significant convergence should be observed among the innovation performance of different countries. On the other hand, if strong countries become stronger and weak countries become weaker in terms of their innovative activities, we should observe divergence.

Using this methodology, we set a simple regression model - see formula (3) - to explore catch up countries. In this model, the output values of a variable for a certain time period ($t-2$) are set as the dependent variable (V_{t2}), which are regressed against the values of the same variable (V_{t1}) during an antecedent period ($t-1$). The item ε_{t2} is also a stochastic disturbance term which is independently distributed from V_{t1} .

$$V_{t2} = \alpha + \beta.V_{t1} + \varepsilon_{t2} \quad (3)$$

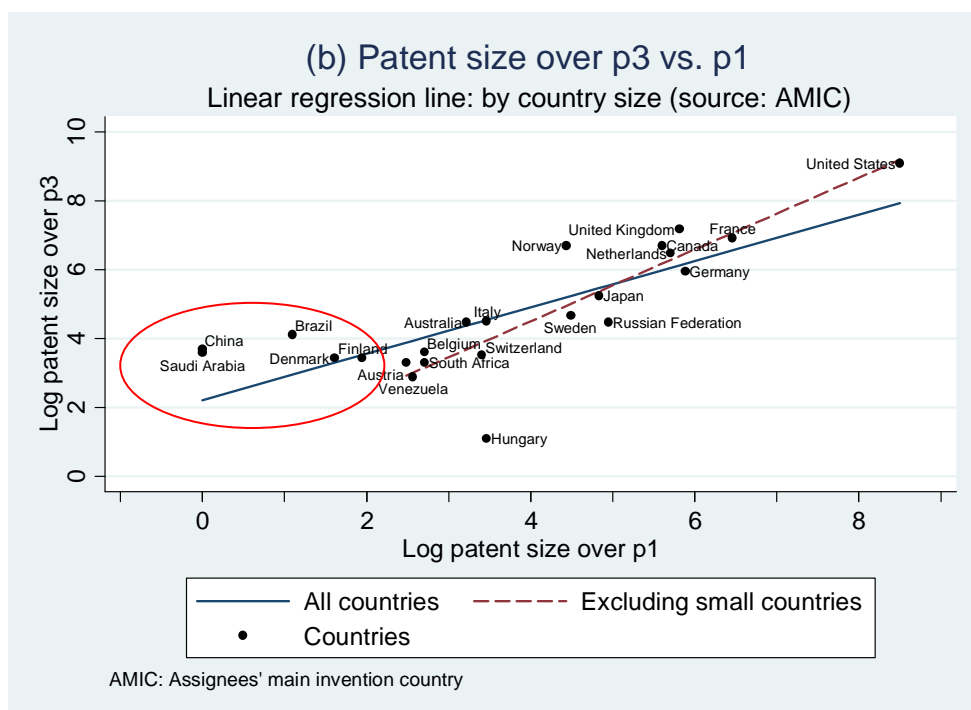
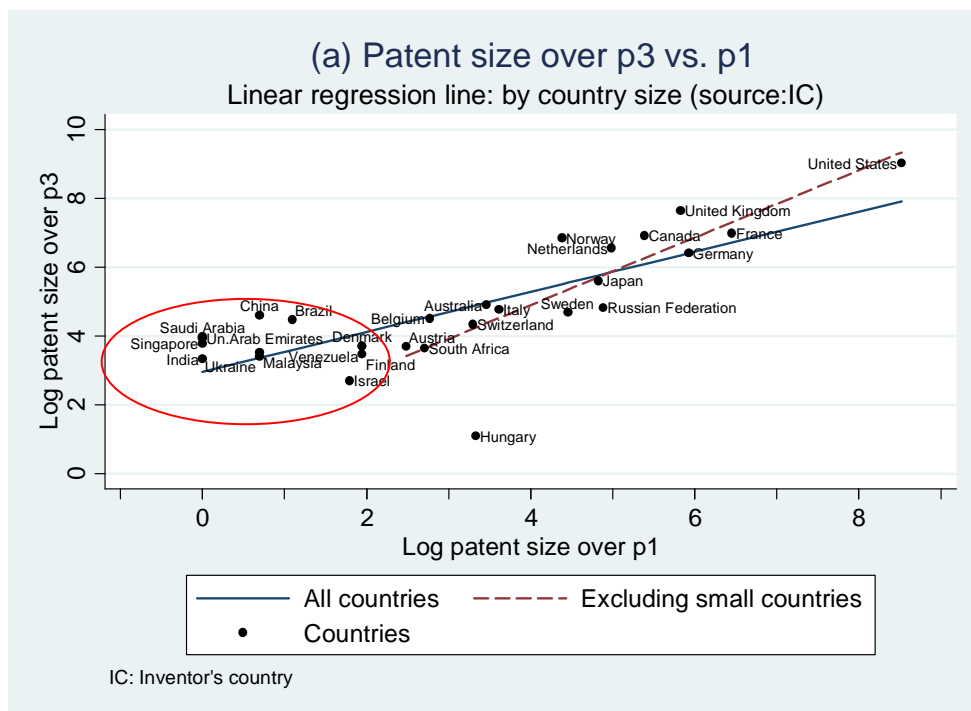
We performed the regression using data related both to country of inventors (IC) and owners (AMIC); results are presented in figure 5(a) and 5(b) respectively. These figures show the scatter plot and fitted regression line (solid line). The results of the statistical tests are provided in table 2. It is evident from the scatter plot that the relationship is relatively linear, the coefficient of the regression model (β) being 0.58 and 0.67 when we use IC and AMIC respectively.

Given $\beta < 1$, we can conclude that on average there has been a convergence process in place (tables 1) where the innovation gap between countries have been decreased. Therefore, some catch-up processes have incrementally taken place between two periods.

A complementary question is which group of countries have caught up reducing their gap with leading countries? According to figure 5, it seems that a cluster of small countries (in terms of innovation size) on the bottom left of the pattern (within the red circle) have improved the position in

p3, as their distance above the line shows. Therefore, they seem to contribute to decrease the β coefficient from unity, rotating the line upward left which supports the convergence and catch up hypothesis. In other words, we observe that a significant portion of regression effect ($1 - \beta$) is attributable to a few and small innovator countries shown by the red circle (defined heuristically when $\log \text{patent size} < 2$).

Figures 5(a) and 5(b) Scatter plot and linear regression of patent size (log): (a) IC; (b) AMIC



In order to evaluate this intuition, we repeated the same test excluding the small innovators in the red circles - see 5(a) and 5(b) - and we summarise results for non-small countries in the table 1. The

dash-line in the figure 5 shows the new regression model. In this case β coefficients are no longer statistically different from unity. Our intuition therefore gets statistical support, which means that we cannot observe convergence and therefore catch up, if the small innovator countries in the red circle are removed from the sample. In other words, relative position of non-small countries in the table have been pretty stable.

The conclusion is that the upstream petroleum industry presents a relatively high degree of cumulativeness at country level and at the same time some incremental change in the share of different countries over time. The direction of these incremental changes has been toward convergence and more equal dispersion of innovative activities from p1 to p3 if all countries of the sample are considered in the analysis, and therefore *catch-up hypothesis* is supported. However, among non-small innovator countries, a persistent pattern is observed where the relative position of different countries among non-small innovator countries remains unchanged.

The difference between the actual patent size of the countries and that estimated by the above regression model (or residual) as expressed in formula 3 is interpreted as the extent of catch-up by different countries. This is a reasonable index because it measures how far countries have gone compared with their peers, considering their relative position in the size distribution. We define the top quartile of the residuals, as the *catch-up range* in order to distinguish more successful countries in building technological capabilities. Given this definition, the catch-up countries are listed in table 2 sorted according to their innovation size. They are listed based on location of inventors.

Table 1 Summary of catch-up statistical tests

Country source:(IC)				
Countries	B	Sig. test ($\beta=0$)	Sig. test ($\beta=1$)	ρ
All	0.58	***	***	0.78
Non Small	0.98	***		0.83
Country source:(AMIC)				
All	0.67	***	**	0.79
Non Small	1.04	***		0.88

* %10; ** %5; *** %1

IC: Inventors' country

AMIC: Assignee's main invention country

We observe two very different groups of technological catch-up countries are recognizable: big players with several hundred patents and small players which at most achieved about 100 patents in p3. There is a huge innovation gap between the two. Except for the US which has always been the leading innovator, only UK, Norway and Canada among big innovators have performed better than average and gained relatively higher shares. These three countries have large innovation bases and have become major contributors to the knowledge base of the industry. On the other hand China, Brazil, Saudi Arabia and United Arab Emirates are included in the catch-up countries, as a small

group, because of a better relative performance among their peers. They have experienced high growth, but from very small or non-existence base. Given their rapid growth, we can call them catch-up countries, but in a very weak sense, because they are still very marginal players in terms of patents.

Another related point is the relatively low and limited number of catch-up countries. This means that escaping from the position dictated by historical pathways, though possible, appears extremely difficult and very limited in this sector. This situation seems very different compared with some other industries like ICT, where the technological catch-up of a relatively large number of countries has been observed (Ernst, 2005). We therefore need to ask what the specificities of the upstream petroleum industry are.

The pattern of catch-up countries and their historical context offer some clues to analyse the reason why only a few countries benefited from technological opportunities which have materialized since mid-1990s.

Table 42 Catch-up countries in upstream petroleum industry

Rank	Country	IPFs in p1	IPFs in p3	ln IPFs in p1	ln IPFs in p3	Residual
	Big innovators	Country source:(IC)				
1	United States	5027	8344	8.52	9.03	1.11
2	United Kingdom	340	2082	5.83	7.64	1.29
3	Canada	218	1016	5.38	6.92	0.83
4	Norway	80	958	4.38	6.86	1.35
5	China	2	99	0.69	4.60	1.23
6	Brazil	3	89	1.10	4.49	0.89
7	Saudi Arabia	0	54	0.00	3.99	1.03
8	United .Arab Emirates	1	51	0.00	3.93	0.97

IPF: International patent families

IC: Inventors' country;

First, all of these catch-up countries are among the major oil producing countries and this include both small and big players. This implies that local demand of petroleum industry is an important driver for innovation catch-up. This is in line with the idea of the geography of opportunities (Stuart and Sorenson, 2003) which are not exploitable by outsiders, even if they have the technical competence to exploit it. However, the very existent petroleum industry as a market pull mechanism for innovation is not a sufficient explanatory variable, as there are many other oil producing countries with high demand for innovation. Yet, they have not joined the club of catch-up countries, even within the small players.

On the other hand, *major* catch-up countries (UK, Norway, and Canada) are among advanced industrial nations which have been producing oil for a long time. This suggest a supportive national innovation system which could deal with diverse range of advanced technologies required in this industry is very critical. Similarly, the limited size of the innovation base of small catch-up countries

implies that without an established wide technological and industrial base, there are serious limits to the degree of catch-up in upstream petroleum.

This pattern suggests that only companies of advanced industrial countries with access to a wide range of both internal and external knowledge sources can cope with the increasing complexity of the innovation processes in this sector. Without access to this pool of accumulated knowledge, oil producing countries may only become marginal innovators.

5. Conclusion: Knowledge base complexity, geography of innovation and catch-up

This article aimed to unravel the relationship between dynamics of knowledge base complexity and the international geography of innovation with particular emphasis on understanding catch-up processes. We argued that it is useful to distinguish between breadth and systemic complexity as characteristic of the knowledge base of a sector, because they imply different geographical patterns of innovation. Relying on empirical evidence from structural change in upstream petroleum industry, this research provides three main contributions to our understanding of the changing geography of knowledge base complexity.

We argued that systemic complexity implies higher geographical proximity, because coordination and integration of different pieces of knowledge is challenging over long distances when there are intensive interactions. However, if the complexity is more of the breadth type and systemic interactions are limited, the possibility of geographical dispersion is higher. This distinction clarifies some of the ambiguities and inconsistencies in the literature with regard to the geographical implications of complexity. In fact, different dimensions of complexity have different geographical impacts.

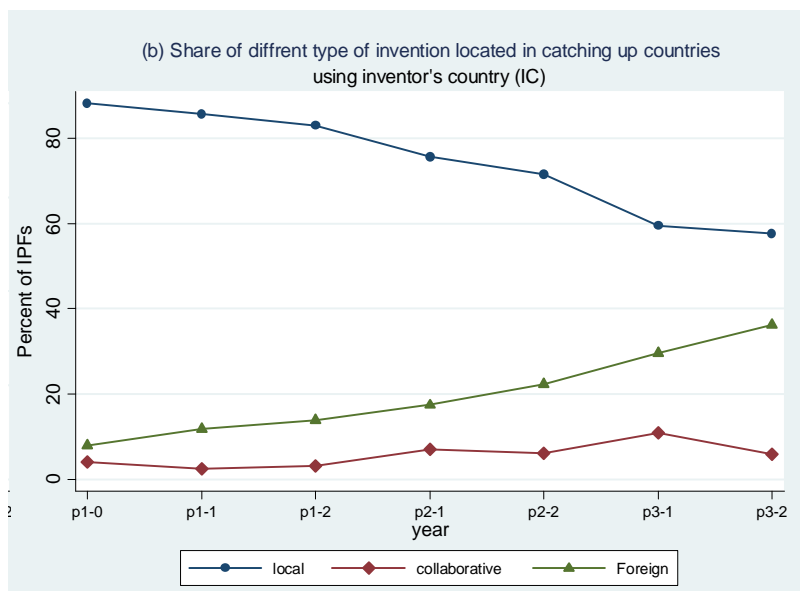
As formulated in our research hypothesis, we expect a higher number of new entries and more opportunities for latecomer catch-up, and therefore more rapid geographical dispersion, when systemic complexity is low and breadth complexity is dominant. In contrast, increasing systemic complexity implies higher barriers to entry, fewer catch-up opportunities, and slower geographical dispersion (or even higher geographical concentration).

We found empirical evidence to support this hypothesis in the upstream petroleum industry. It is shown that increasing breadth complexity in p1 provides wider opportunities for catch-up of other countries and more rapid geographical dispersion. In this period, new individual technologies (like horizontal drilling, 3-D seismic, etc.) are introduced. As they are in their early stages and entry barriers are relatively low, potential players may enter to the sector and become influential innovators.

In other words, when breadth complexity is dominant, it is likely that companies innovate in one segment of the industry *without* access to the knowledge of the other parts. In these conditions, we

can observe more equal dispersion (less concentration) of innovation, even without internationalization of companies. This is compatible with foreign patenting trends shown in figure 6, where there was a very limited internationalization in p1. Therefore, a large part of the more equal geographical dispersion of innovation (figure 4) in p1 should be attributed to local innovations in catch-up countries.

Figure 6 Share of different type of inventions according to ownership



Local: Patents invented in a country and also owned by companies of that country.

Foreign: Patents are invented in a country, but assigned to the foreign companies operating in the host country

Collaborative: Patents which are invented in a country, but co-owned by companies of that country and companies of other countries.

In contrast, we observe increasing systemic complexity slows down geographical dispersion in p3. When systemic complexity is in place, coordination and integration of knowledge over large distances may become a critical issue and disintegrated structures may not be sufficient. The internal structure of big vertically integrated companies becomes advantageous for integration of the increasingly diverse range of knowledge domains involved in complex projects. However, relevant segments of knowledge may be geographically dispersed in different specialized locations and clusters. Therefore organizational and cognitive proximity (Boschma, 2005) matters more to cope with systemic complexity over geographical distance.

When systemic complexity increases, the leading companies in the sector which largely originate from industrial advanced countries are better placed than other companies to innovate. They have access to a diverse range of geographically distributed knowledge both in their home countries in abroad. They also benefit from internal integration capability over large distances which enable them

to “go global” as a result of their international competitiveness (Bridge and Wood, 2005). In other words, if there is not strong internal capability, it is not possible to take advantage of globally available knowledge in the innovation processes.

Cantwell (1995) uses the term new “globalization of technology” to describe this new recent situation in contrast with the earlier ‘internationalization’ hypothesis. *Internationalization* happens when “the peculiarities of foreign production conditions and demand have required leading MNCs historically to develop innovations abroad, related to those that had been pioneered at home” (Cantwell, 1995, p.171). However, according to Cantwell (1995), when a strategy of *globalization of technology* is followed, leading companies develop “internal international networks to exploit the locationally differentiated potential of foreign centres of excellence” (p. 155). They seek to integrate local and global knowledge sources through their integrated networks to cope with the increasing systemic complexity. Therefore, the key feature of the globalization era is that integration and connection of different pieces of knowledge produced in different parts of the world becomes much more important in innovation processes.

We measured the rising intensity of knowledge flows between home and abroad in the innovation process, which is a signal of transition from internationalization to globalization of innovation. Percentage of patents owned by companies of each country which is invented by at least one inventor located in the home country and one inventor located abroad (Co-inventor patents), are considered as a proxy for international knowledge interactions. This figure achieved to about 20 percent in p3, from a negligible share in p1 supporting our idea about shift to “new globalization” which is compatible with the rise of systemic complexity.

In spite of increasing systemic complexity in the sector, there were a few catch-up countries which managed to reduce their gaps with leaders and improve their position, taking advantage of emerging innovation opportunities. It seems that, co-existence of local sectoral production as a demand side for innovation and supportive national systems of innovation in the supply side are preconditions both to recognize these innovation opportunities and exploit them. Without these preconditions, it is very unlikely that companies from latecomer countries in the sector will overcome the cognitive barriers. In addition, the results suggest that in dealing with systemic complexity, the cognitive and organizational proximity available in internal networks of big multinational companies may be more important than geographical proximity.

The empirical results also offer some theoretical insights about the dynamics of geographical patterns of innovation. We observed a correspondence between dynamics of geographical patterns of innovation and the dynamics of knowledge base complexity. The knowledge base of the industry evolves from the state of relative *simplicity* before p1, to the dominance of *breadth* complexity in p1,

and then *systemic* complexity in p3. In parallel, the geographical dynamics of innovation move from relative *non-internationalization* before p1, to *internationalization* over p1 and finally to a *new globalization* of innovation in p3. Although we are not offering a deterministic relationship, these findings offer valuable insights regarding the development of a dynamic theory of the geography of knowledge base complexity, as an interesting area for further research.

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